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AERODYNAMIC FORCES ON VARIOUS CONFIGURATIONS OF RAILROAD CARS FOR CARRYING TRAILERS AND CONTAINERS

Wind Tunnel Tests of Six Scale Model Configurations

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FINAL REPORT

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Wind tunnel tests of models of intermodal railcar configurations to establish feasibility of test methods and provide comparitive data on 6 car configurations. (See also Aerodynamics of Freight Trains, FRA/ORD 76/295 Volumes I through IV)

16. Abstract

* Toward improving the energy efficiency of rail intermodal service, the aerodynamic characteristics of the rolling stock offer a significant opportunity for betterment. At speeds above 45 miles per hour more than half of the resistance of an intermodal train is caused by the aerodynamic drag of the cars and their loads. Methods by which the aerodynamic drag may be minimized are, therefore, of considerable interest to railroads and car designers.

This report covers the wind tunnel testing of scale models of railcars for carrying trailers and containers. The purpose was twofold: First, to determine whether significant differences in the aerodynamic characteristics of such scale models could be measured in the wind tunnel showing that it could be utilized as an evaluation tool in future railcar design programs and, second to obtain comparative performance data on five new intermodal railcar configurations.

The findings confirm that wind tunnel testing is a viable design evaluation method. The cost of this series of tests was about $9000 for the wind tunnel utilization, about $20,000 for the models plus a nominal amount for the data analysis and report preparation. Compared to full scale testing, wind tunnel testing, therefore, requires only minimal resources.

From the data collected, differences between the aerodynamic characteristics of existing and developmental configurations are apparent. The configurations for which data was obtained include:

- Conventional TTX Car
- Santa Fe Fuel-Foiler (10 Pack)
- Trailer Train 2-unit Prototype Car
- Paton Low-Pro Car
- Southern Pacific Double-Stacked Container Car
- BiModal Roadrailer

Tests included comparisons between the cars when carrying trailers of 40 feet and 45 feet in length when moving in both the nose forward and doors forward orientations and provided notably different results. Containers of 40 feet and 35 feet lengths were also tested on cars capable of carrying them.

Worthy of particular note is the influence of air moving across the train as denoted by yaw angles of values other than zero. Combinations of train speed and ambient air movement which produce a resultant relative wind vector of 10° or greater were shown to increase aerodynamic drag by as much as 75% on some configurations. Reduction of susceptability to crosswinds therefore, appears to be a high-payoff design goal for new intermodal railcars.

(*Prepared by Test Sponsor)

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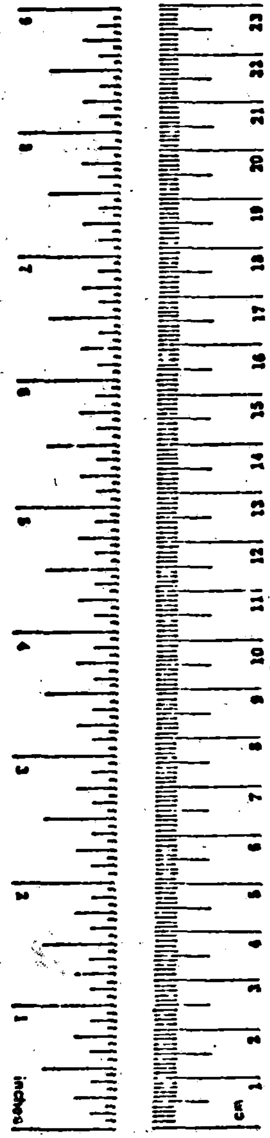
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

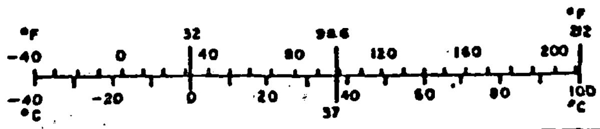
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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NOMENCLATURE

$C_A A$	Axial force area
n	Number of units in car
q	dynamic pressure
V_R	Relative wind velocity
V_t	Train velocity
V_w	True wind velocity
α	Wind angle
ψ	Yaw angle

Subscripts:

L	Leading unit
M	Middle unit
T	Trailing unit

Note: Leading - Unit in lead when going forward
Middle - Unit in middle
Trailing - Unit in rear when going forward

INTRODUCTION

The development of multimodal freight systems has led to the conception of several new multimodal railroad car designs. This report describes a series of wind tunnel tests performed to obtain the aerodynamic characteristics of these cars and a comparison with the TTX car which was extensively tested in Reference 1. Five new configurations were tested:

Trailer Train Prototype	40 and 45 ft. trailers
Santa Fe 10 Pac	40 and 45 ft. trailers
Paton Lo Pro	40 and 45 ft. trailers 35 and 40 ft. containers
Roadrailer	45 foot trailers
Southern Pacific Double Stack Articulated Container Car	40 ft. containers

Three of the configurations were for trailers only. The Paton Lo Pro accomodates both trailers and containers, and the Southern Pacific Double Stack is for containers only. Most of these concepts also employ articulated cars made up of units of about 45 feet in length. The Santa Fe 10 Pac employs ten such units to form a car; the Paton Lo Pro, six units; the Southern Pacific Double Stack, three units; and the Trailer Train Prototype, two units.

TESTING METHODS

The tests were run in the 10 foot GALCIT Wind Tunnel at the California Institute of Technology in Pasadena, California (CIT). The technique used was similar to that used in the tests reported and discussed in References 1 and 2. A ground plane was installed across the wind tunnel and the model train mounted on a track on the ground plane. The track was attached to a yaw table that could be used to yaw the model up to an angle of 30°. The train tested consisted of a locomotive (GM SD45-2), from three to six units of the configuration in question, and a final boxcar. The restraints of the wind tunnel require that the train tested be considerably shorter than an actual consist. The models were 1/43 scale resulting in a total train length of about 9 ft. Depending on the configuration, one or two units of the type being tested were located on the balance which measured the six components of force and moment. The test configuration was designed to place the units located on the balance (called the metric units) in a typical location with respect to the surrounding units that they would occupy in a typical train. The implicit assumption was made that only a few of the units ahead of and behind the metric units were important in effecting the flow about the metric units. The assumption was required by the limited length of the wind tunnel test section. A trade off had to be made between the number of units in the train tested and the scale of the models. The 1/43 scale was selected because model trailer kits were available in this scale and it was sufficiently close to the 1/48 scale used in O gauge railroad models such that O gauge wheel trucks could be used on the models.

The multiunit cars of these configurations posed problems which had not been involved in the previous configurations tested. Since an entire car was too long to fit on the existing balance assembly and also too long to fit in the wind tunnel (along with additional units ahead and behind) it was decided to test the car by units. Two units of approximately 45 feet scaled length which was the unit length of all of the configurations except the Southern Pacific Double Stack would fit on the balance. The Southern Pacific Double Stack units were about 60 feet scaled length and only one unit was located on the balance at a time. The tests had to be designed so that the units on the balance were surrounded by the proper units and every configuration of metric units and surrounding units which exist in the actual configuration was modeled. To accomplish this only one configuration of units was required for the Trailer Train Prototype, three for the Santa Fe 10 Pac, two for the Paton Lo Pro, one for the Roadrailer, and three for the Southern Pacific Double Stack.

This system of testing had the advantage that it determined the forces on individual or small numbers of units. This allows the force on a variety of car configurations made up of different numbers of these units to be determined from this one set of tests. The axial force, which is probably the one of greatest interest, for the entire car or for an entire train of like cars, can be determined by adding together the axial forces measured in the individual tests. Other forces such as lift and side force and the rolling moment are of greatest interest for individual units. While the individual units of a car offer some restraint on each other relative to being blown off the track, the restraint is limited and it is useful to know the effect on each individual unit. The disadvantage to this mode of testing is that it is more complicated and requires a greater number of tests to achieve the results for a complete car.

The wind tunnel configuration is shown in Figure 1. The metric bar is 21 inches long and mounted in a slot along the centerline of the track. It is set at a level slightly below that of the track. The opening is then bridged with a thin sheet of metal with holes through which pass the hold-down screws of the various units mounted on the balance. In this way the balance plate is shielded from the air flow. The cars are supported sufficiently high so that their wheels are slightly raised above the track to prevent contact with the metal cover plate.

Aerodynamic theory and practice has established that aerodynamic forces on objects scale as the dynamic pressure of the air flow, one half the air density times the velocity squared. Tests at different velocities can be correlated if the actual forces are divided by the dynamic pressure to form a number which has the dimensions of area. Once this force area has been determined for tests at one velocity it can be used to predict forces at any velocity by multiplying the force area by the appropriate dynamic pressure. This same concept can be applied to moments. In this case the number obtained by dividing the moment by the dynamic pressure has the dimensions of area. To facilitate in this process Table 1 shows dynamic pressure as a function of relative wind velocity for sea level conditions. For instance, if the axial force area were 20 square feet, the axial force at 50 mph would be 6.384 pounds per square foot times 20 square feet equalling 127.7 pounds. At 70 mph, the dynamic pressure would be 12.513 pounds per square foot and the force 250.3 pounds.

TEST CONFIGURATIONS

The Trailer Train Prototype is a two unit car, each capable of carrying a 45 foot or shorter trailer. Both units of the car were mounted on the balance and two additional two-unit cars were used ahead of and behind the metric unit in addition to the locomotive and boxcar at either end of the train. Drawings of the models are shown in Figure 2, the locations of the trailers and cars as mounted in the wind tunnel in Figure 3, and a picture of the configuration mounted in the wind tunnel in Figure 4. The car was tested with both 40 and 45 foot trailers on all units and for travel in forward and backward directions.

The Santa Fe 10 Pac is a ten unit car which can carry 40 and 45 foot trailers, Figure 5. The two end units are different than the eight middle units. The end units are identical except that they are turned in opposite directions. The result is that the trailer on the rear unit faces in the opposite direction from the trailers on the other nine units resulting in a different gap between the trailer on the ninth and tenth unit. Three middle and two end unit models were constructed. This car had to be tested in the following manner:

Forward Units	Metric Units	Trailing Units
Forward tests:		
Leading, middle	Middle, middle	Trailing
Middle, middle	Middle, trailing	Leading
Middle, trailing	Leading, middle	Middle
Backward tests:		
Trailing, middle	Middle, middle	Leading
Middle, leading	Trailing, middle	Middle
Middle, middle	Middle, leading	Trailing

The rationale behind setting up this arrangement was so that the metric units would always be preceded by two units and trailed by one which correctly simulated the real situation. The spacing for the trailers and car units mounted in the wind tunnel is shown in Figure 5. Photographs of the configurations are shown in Figure 6. The car was tested with both 40 and 45 foot trailers and for travel in the forward and backward directions.

The Paton Lo Pro is a six unit car designed to carry 40 and 45 foot trailers as well as 20, 35, and 40 foot containers. The car consists of four middle units, a leading and a trailing unit. All the trailers face in the same direction. Models of a leading, trailing, and three middle units were constructed, Figure 7. These units were tested in two different arrangements as follows:

Forward Units	Metric Units	Trailing Units
Forward tests:		
Leading, middle	Middle, middle	Trailing
Middle, middle	Trailing, leading	Middle
Backward tests:		
Trailing, middle	Middle, middle	Trailing
Middle, middle	Leading, trailing	Middle

The spacing of the trailers and containers on the cars are shown in Figure 8. Photographs of the configurations are shown in Figure 9. This car was tested with 40 and 45 foot trailers, 35 and 40 foot containers and for travel in the forward and backward directions.

The Roadrailer configuration consists of identical units which are used to form a train. They are all 45 foot units. For these tests, two units were mounted on the balance with two units ahead and two units behind. A drawing of the Roadrailer and the spacing in the wind tunnel is shown in Figure 10. Photographs of this configuration are shown in Figure 11. These units were tested in the forward direction only since the developer has not indicated the feasibility of high speed line haul operations in the backward direction.

The Southern Pacific Double Stack is designed to carry 40 foot containers only. It is a three unit car consisting of two end units and one middle unit, Figure 12. The configuration was tested in three tests locating each unit on the balance as follows:

Forward Units	Metric Units	Trailing Units
Leading	Middle	Trailing
Trailing	Leading	Middle
Middle	Trailing	Leading

The spacing of the units is shown in Figure 10 and photographs in Figure 13. Since this unit is symmetric it was only tested in one direction.

The TTX car had previously been tested with 40 foot trailers in both the forward and backward directions and with 40 foot containers in one direction. A check run was made with this configuration using 40 foot trailers traveling in the backward direction. A drawing of the TTX car along with a photograph in the wind tunnel is shown in Figure 14. Other than this, the results from the previous testing, Reference 1, will be used in this report. In comparing the results presented in this report to those in Reference 1 please note that these results are half as large because they are per trailer and not per car.

TEST RESULTS

The wind tunnel results are shown in tabular form for axial force area, Table 2; lift force area, Table 3; side force area, Table 4; and rolling moment volume, Table 5. These tables show the results for the different units mounted on the balance.

In order to combine these results for the different units into that for a multiunit car, it is necessary to add together the different results. The following relations are used to obtain axial force results for complete cars.

Santa Fe: The results obtained here are only appropriate for a car of four units or greater. The appropriate relation is

$$C_AA = (C_AA)_{LM} + \frac{n-4}{2}(C_AA)_{MM} + (C_AA)_{MT}$$

where n is the total number of units. n would be ten for the 10 Pac configuration.

Paton Lo Pro: From this data, axial force can be determined for cars of four or more units. The appropriate relation is

$$C_A A = (C_A A)_{TL} + \frac{n-2}{2}(C_A A)_{MM}$$

n equals six is the configuration shown by Paton.

Southern Pacific Double Stack: This data can be used to determine the axial force on cars of three units or longer. The appropriate relation is

$$C_A A = (C_A A)_L + (n-2)(C_A A)_M + (C_A A)_T$$

A three unit car is the configuration used by Southern Pacific.

Trailer Train Prototype: The results are only appropriate for the two unit car as used by Trailer Train.

Roadrailer: The results are appropriate for single units and applied to as many of these units coupled into a train as desired.

TTX: The TTX car was tested as a single unit and the results have been presented in Reference 1. In this present series of tests, a check run was made to compare with these previous results and this comparison is presented in Appendix B.

Special formula for obtaining the axial force area for cars that were tested as separate units have now been given. These formula have not been included for cars that were tested as complete units since they do not appear to be necessary. Once the force area for a car has been obtained, the force area for trains made up of these cars can be obtained by multiplying the value for one car by the number of cars.

AXIAL FORCE

Using these relations, the tests of the various units have been used to find the axial force on the entire car of the number of units suggested by their developers. The force on the entire car is then divided by the number of trailers or containers carried to arrive at an axial force per trailer or container. This is done since the cars are of different size and it is not meaningful to compare them on a car for car basis. This axial force is also the axial force per unit since each unit carries only one trailer or container except for the Southern Pacific which has two containers per unit. The axial force per container or trailer is shown in Figures 15 - 20. Two ordinate scales are used to give the force as a force area and as the actual force assuming 70 mph relative wind velocity. In these figures, the attempt has been made to group the results for the different configurations together on the same figure to facilitate comparison between different ways of loading or operating a particular type of equipment. Another presentation of these same results is shown in Figures 21 - 23. Results for the different configurations are grouped together according to the type of load carried, 45 foot trailers, 40 foot trailers, and containers.

Figures 21 - 23 provide an easy way to assess the aerodynamic efficiency of the various designs. These figures show the advantage of having the trailers facing forward rather than backward. This is because the forward corners of the trailers are rounded and the rear corners are sharp. This difference can be as large as the difference between configurations. For the 45 foot trailers Figure 21 shows that the most efficient is the Roadrailer and the least efficient is the Trailer Train Prototype. The Santa Fe 10 Pac and the Paton Lo Pro are about the same except that the Paton Lo Pro is poorer backwards at large angles or yaw. The lower profile of the Paton Lo Pro is apparently compensated by the shorter length per unit and increased number of units per car for the Santa Fe 10 Pac. The greater spacing between trailers probably accounts for its higher axial force at larger angles of yaw. For the 40 foot trailers, Figure 22, the relations between the various designs remain about the same. However, the Paton Lo Pro tends to be somewhat better with respect to the Santa Fe 10 Pac for the 40 foot trailers than for the 45 foot trailers. The axial force is generally higher for the 40 foot trailers than for the 45 foot trailers for all designs. This can be seen more easily in Figures 15 - 17. The TTX car compares favorably with the newer designs for carrying 40 foot trailers. The new configurations are designed to carry 45 foot trailers and are less efficient when carrying 40 foot trailers. The comparison for containers is limited to only three designs, the Paton Lo Pro, the Southern Pacific Double Stack, and the TTX. The Paton Lo Pro and the Southern Pacific Double Stack are about the same when the Southern Pacific Double Stack is carrying only one container per unit. When it is loaded with two containers it clearly has lower axial force per container. At first it might seem that the Southern Pacific Double Stack with a two container load was aerodynamically inefficient because of its height. On further reflection it seems reasonable, and is born out by the tests, that the additional container only adds the frontal area of the container and does not double the axial force while doubling the number of containers. The Southern Pacific Double Stack car does have the disadvantage that it has a large axial force when empty. This is because of the bulkheads at the front and the rear of each unit. The importance of this effect will depend on the amount that this car must be run in the empty condition. The TTX car gives considerably lower drag than the Paton Lo Pro and only a little more than the Southern Pacific Double Stack. The poor relative performance of the Paton Lo Pro is caused by the fact that it is not lower than the TTX car when carrying containers but is considerably longer with large gaps between the containers.

LIFT, SIDE FORCE, AND ROLLING MOMENT

Lift, side force, and rolling moment do not have a primary effect on the efficiency of the train but can contribute to catastrophic events such as derailments. For these forces and moments, an average over all the units of a car does not seem to be the best since an individual unit could be derailed if the forces on it were too high (there is only limited restraint between the different units). Since in several cases the forces on multiple units have been measured together, it may be necessary to make certain assumptions in determining the forces on the separate units. For the Trailer Train Prototype, the force on the two units has always been measured together and there is no way of separating between the forward and trailing unit. For the Santa Fe 10 Pac, the force on a middle unit can be taken as half the force measured on two units. The force on the leading and trailing cars can then be determined by subtracting the force on a middle unit from the combined measurement of the leading middle units and middle trailing units to obtain the forces on the leading and trailing units only. For the Paton Lo Pro the force on a middle unit is half the force on the two middle units. In order to separate the forces on the leading and trailing units the assumption has been made that the forces on the trailing unit are the same as on the middle unit and the forces on the leading unit are then obtained by subtraction. Results from the tests of the Santa Fe units seem to bear out this assumption. For the Southern Pacific Double Stack the forces on the individual units were measured and the Roadrailer units are all similar, so there is no problem with either of these configurations.

Tables 3 - 5 show the lift, side force, and rolling moments on the various units as tested in the wind tunnel. All of these forces and moments are small at zero yaw angle. The side forces and rolling moments should be precisely zero at this condition. For the lift forces a positive value shows an upward force. At zero yaw the forces are generally small compared with the values at large yaw angles and some tests show negative values. The tests were not designed to measure these small values and little significance should be attached to them and to the variation in the sign. If the train is truly symmetric and at zero yaw angle, symmetry arguments require that the side force and rolling moment be zero. Most of the zero yaw angle results in the two tables for side force and rolling moment show negatives. The definition of positive and negative in these two quantities as well as the yaw angle is, of course, arbitrary. They have been chosen such that at a positive yaw angle a side force towards the lee side of the vehicle is called positive and the rolling moment caused by such a force is also positive. The predominance of negative side forces and rolling moments at nominal zero yaw angles indicates most likely that this was not precisely zero yaw angle but probably slightly negative. The magnitude, relative to the magnitude at larger yaw angles, shows that small errors in yaw angle would account for these results. There are other explanations such as the cars not being precisely lined up with each other that could account for these effects. The readings at zero yaw angles cannot be considered a significant aerodynamic result and as such should be ignored.

The lift, side force, and rolling moments expressed as force areas and moment volumes and also as forces and moments at 70 mph relative wind velocity for the different configurations are shown in Figures 24 - 38. The general conclusion is that the higher configurations give higher lift, side force, and rolling moments.

The rolling moments result from a combination of forces which include the side and lift forces. The rolling moments act about the longitudinal center-lines of the vehicles as projected in the plane defined by the tops of the rails. This data would be useful in performing analyses of vehicle stability wherein the critical cross wind conditions for rollover are to be estimated. It should be noted that due to dimensional limitations of the tunnel, data was acquired for yaw angles only between 0 and 30 degrees. Rolling moment data for the range of from 30 to 90 degrees would be necessary to fully study the cross wind stability issue.

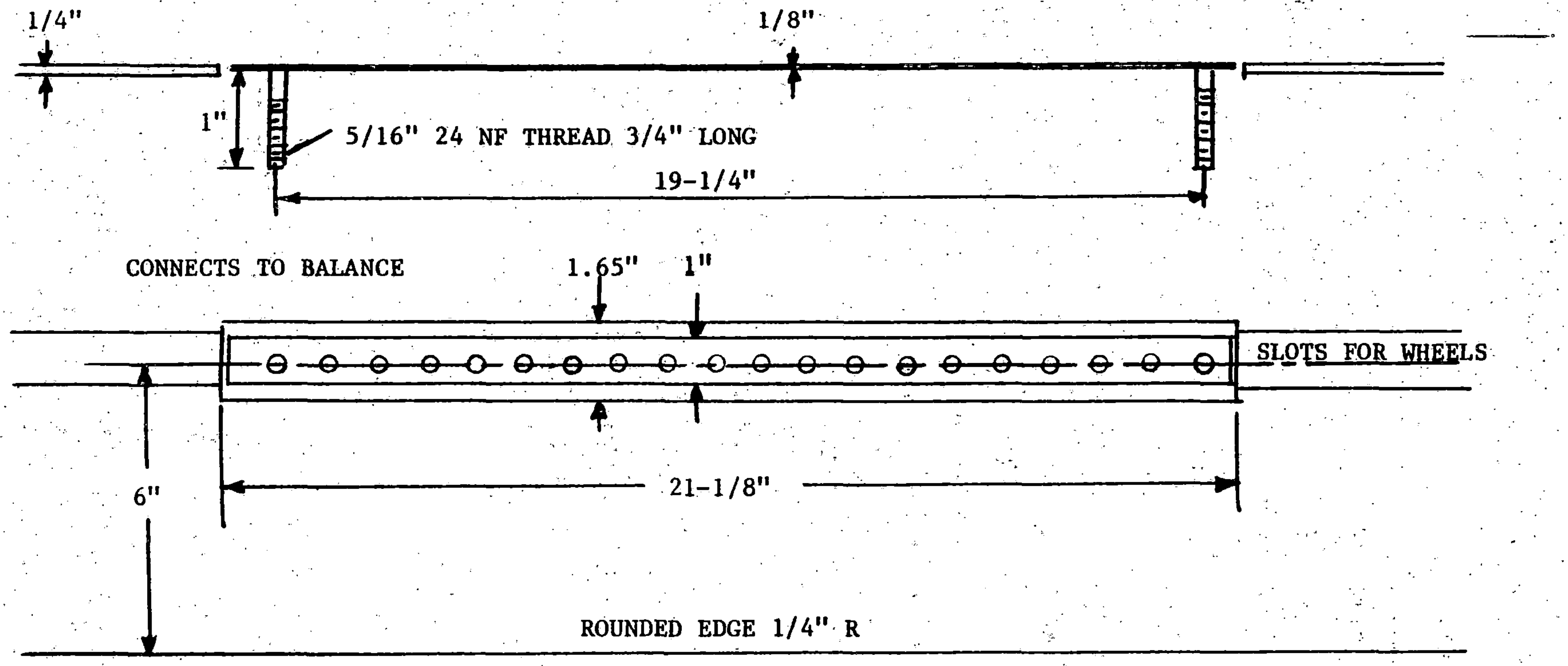


Figure 1. Balance Mechanism for Mounting Models in Wind Tunnel.

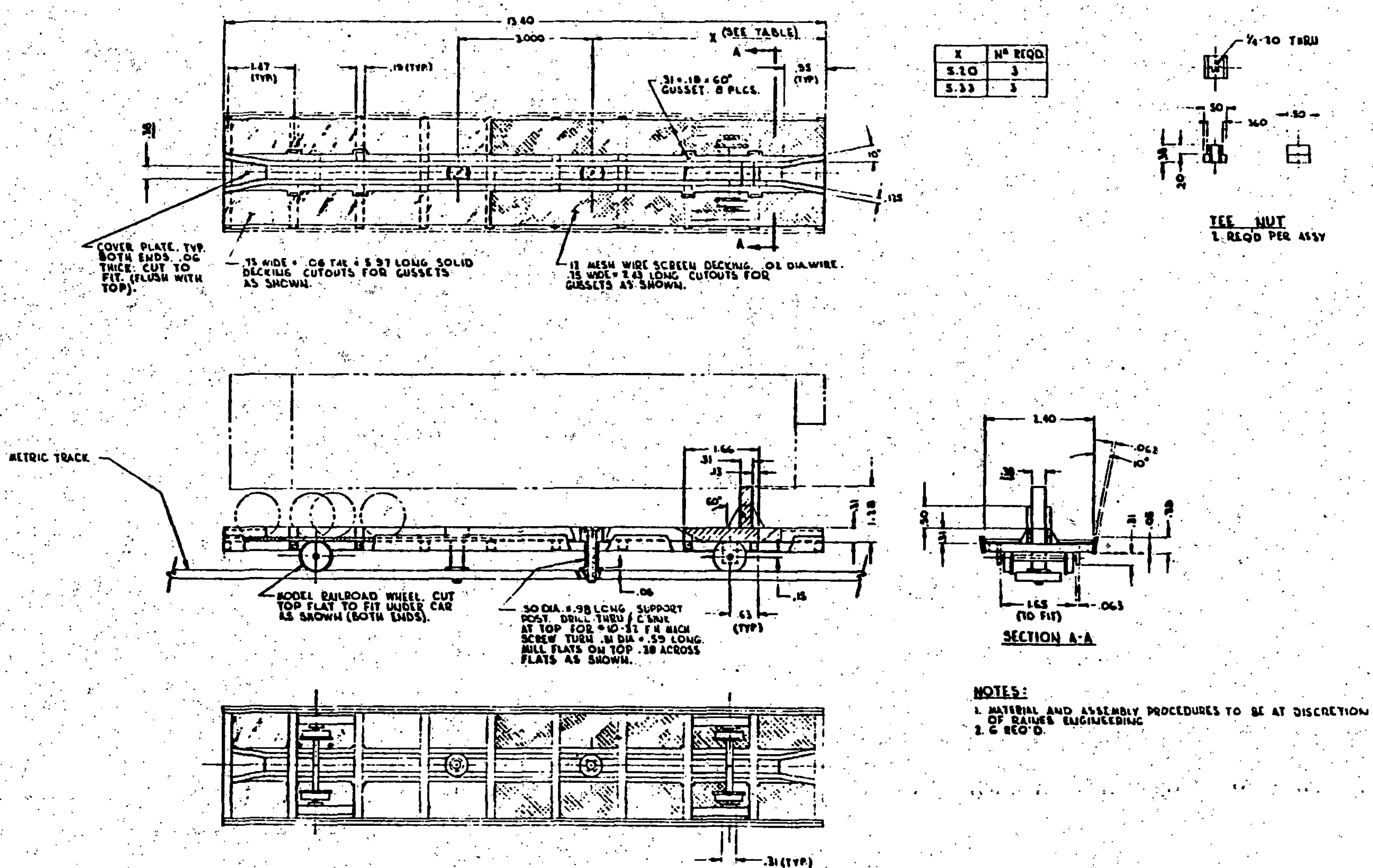


Figure 2. Drawing of Model for Trailer Train Prototype Unit of Two Unit Car. Six constructed.

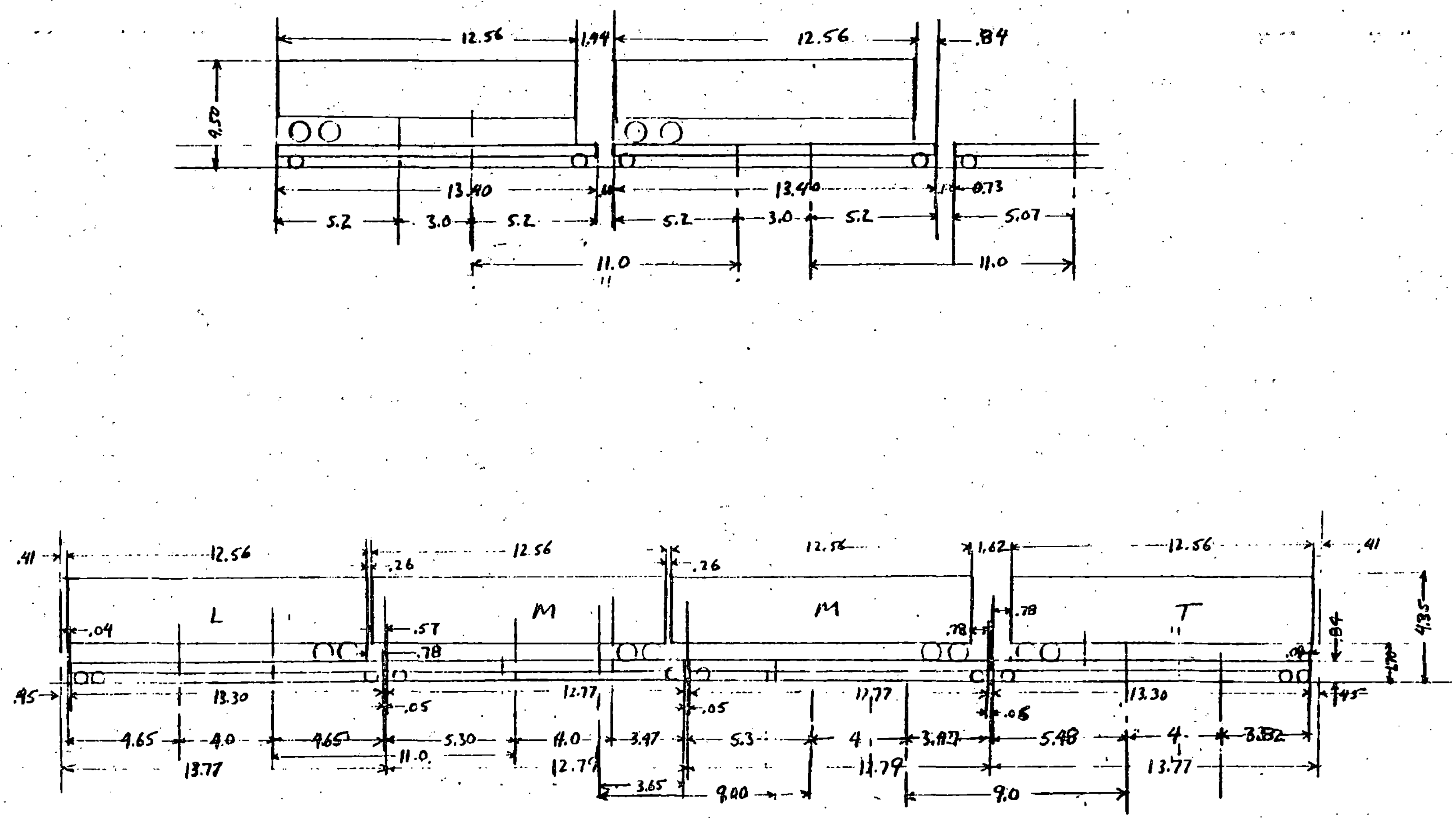
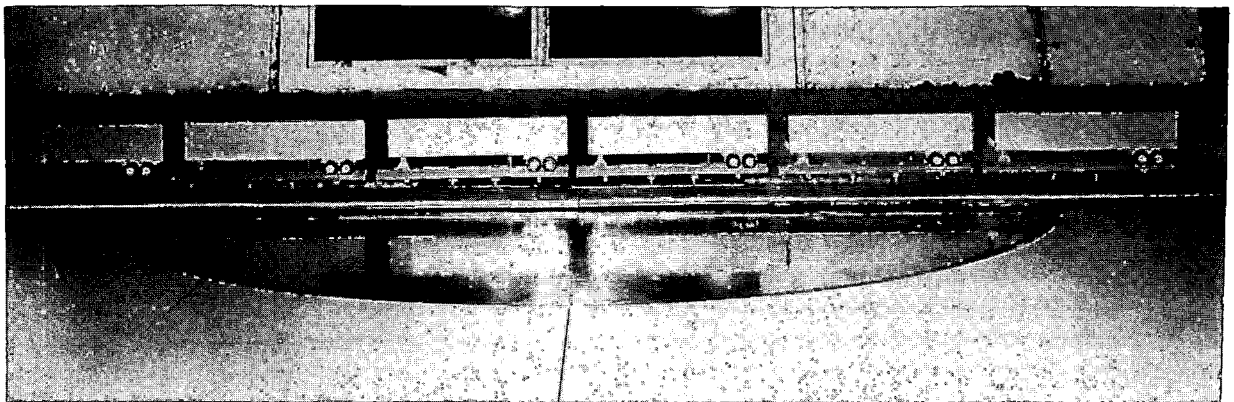
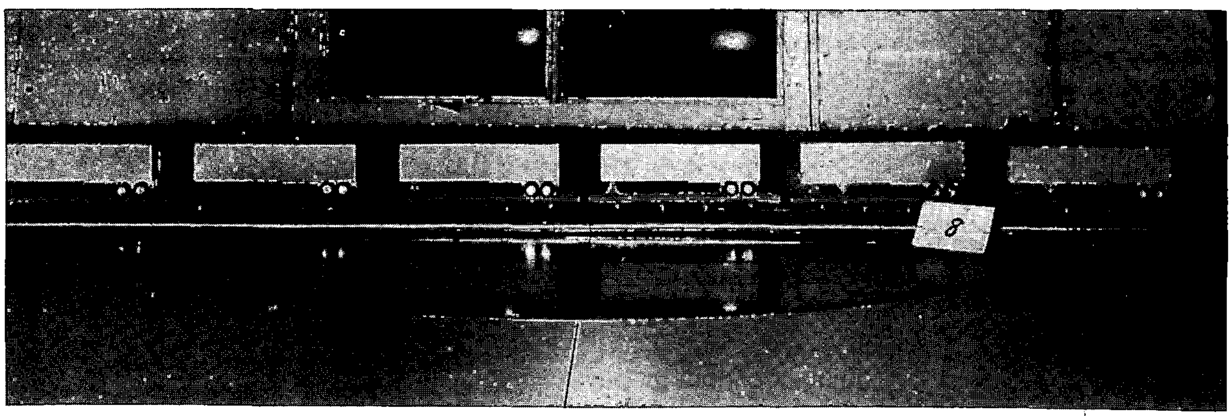


Figure 3. Top - Location of Trailers Mounted on Trailer Train Prototype Car and Relation Between Units of Car as Mounted in the Wind Tunnel. Bottom - Location of Trailers on Santa Fe 10 Pac Car and Between Units of Car as Mounted in the Wind Tunnel.



45' Trailers



40' Trailers

Figure 4. Trailer Train Prototype Model in Wind Tunnel.

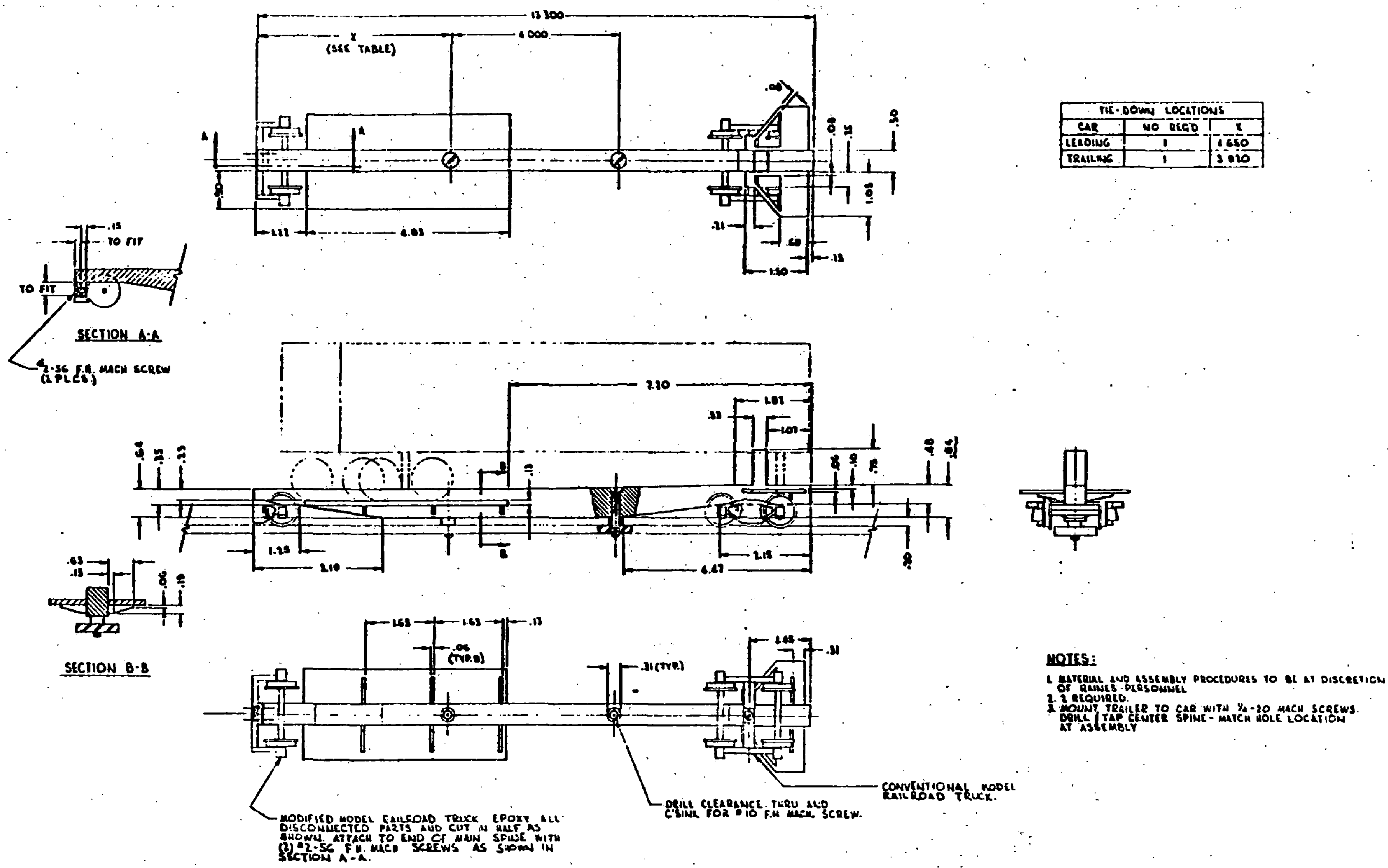


Figure 5a. Drawing of Model for Santa Fe 10 Pac Car. Leading and Trailing Unit. Two constructed.

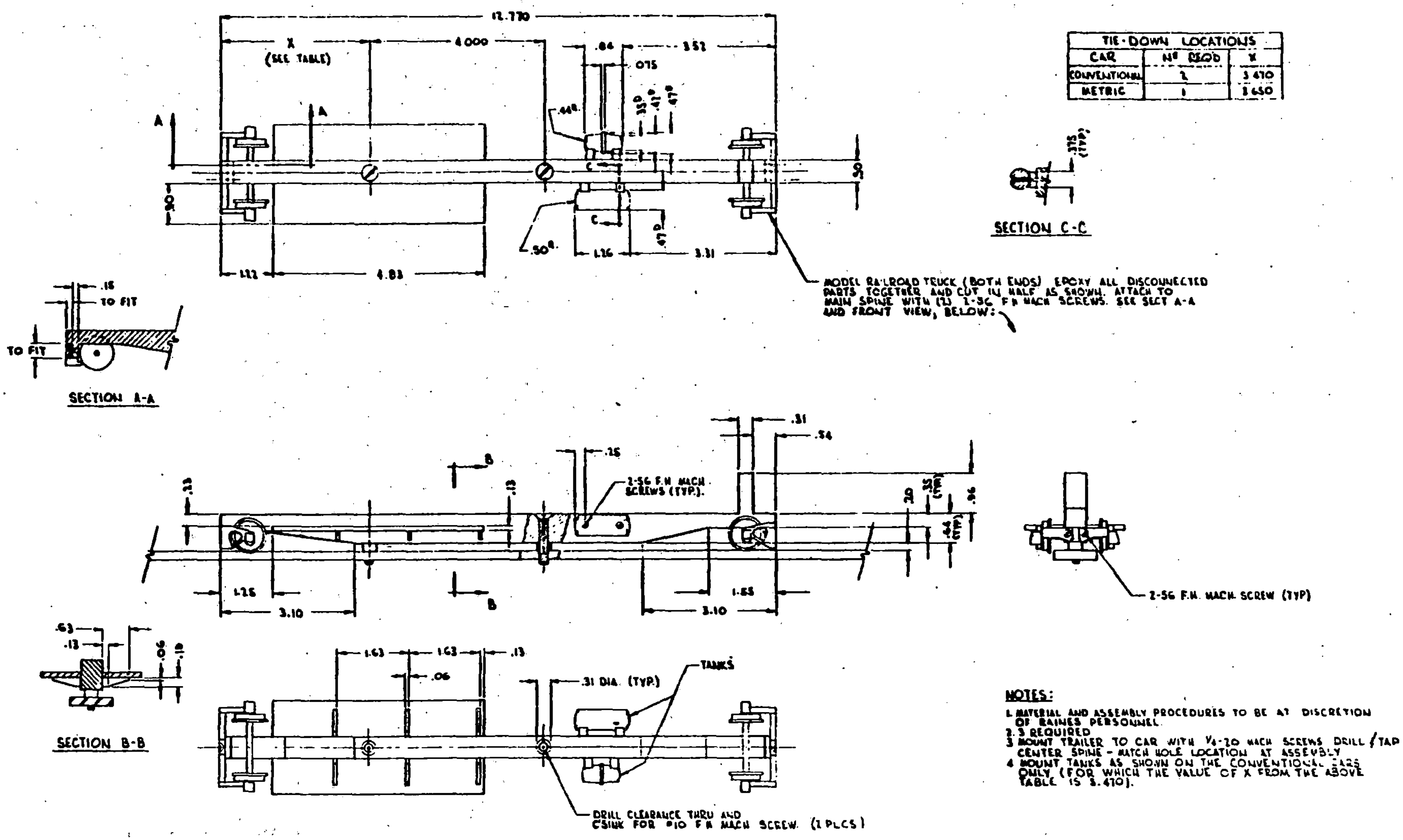
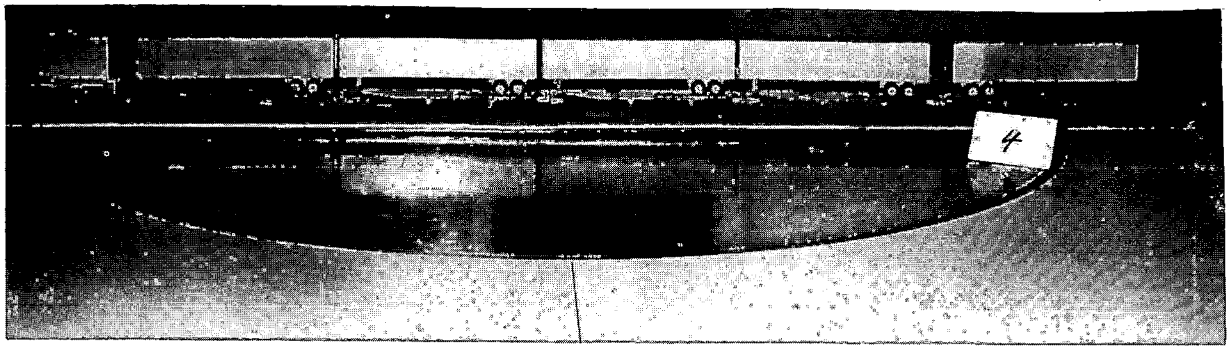
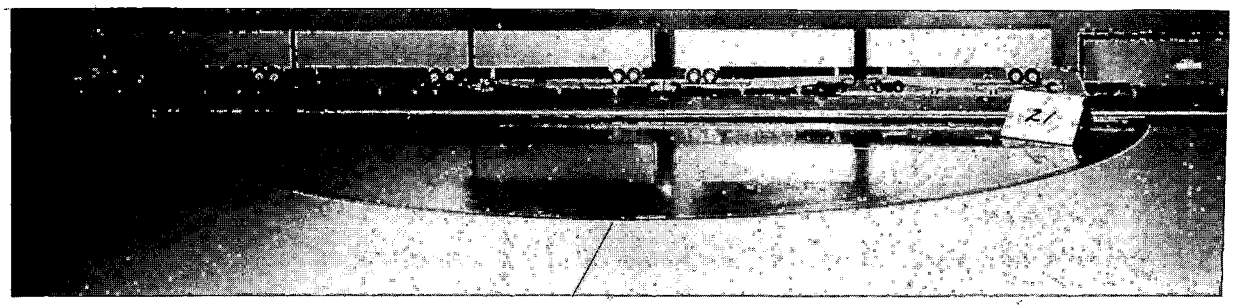


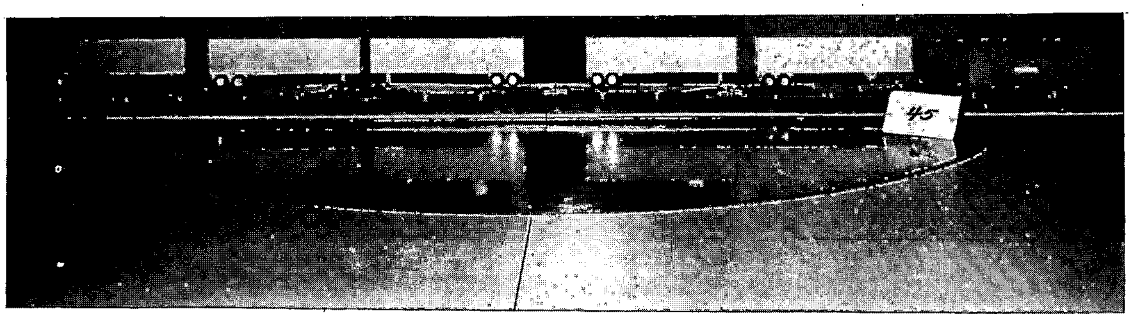
Figure 5b. Drawing of Model for Santa Fe 10 Pac Car. Middle Unit. Three Constructed.



Two Middle Units on Balance, 45' Trailers



Middle and Trailing Units on Balance, 45' Trailers



Leading and Middle Units on Balance, 40' Trailers

Figure 6. Santa Fe 10 Pac Model in Wind Tunnel.

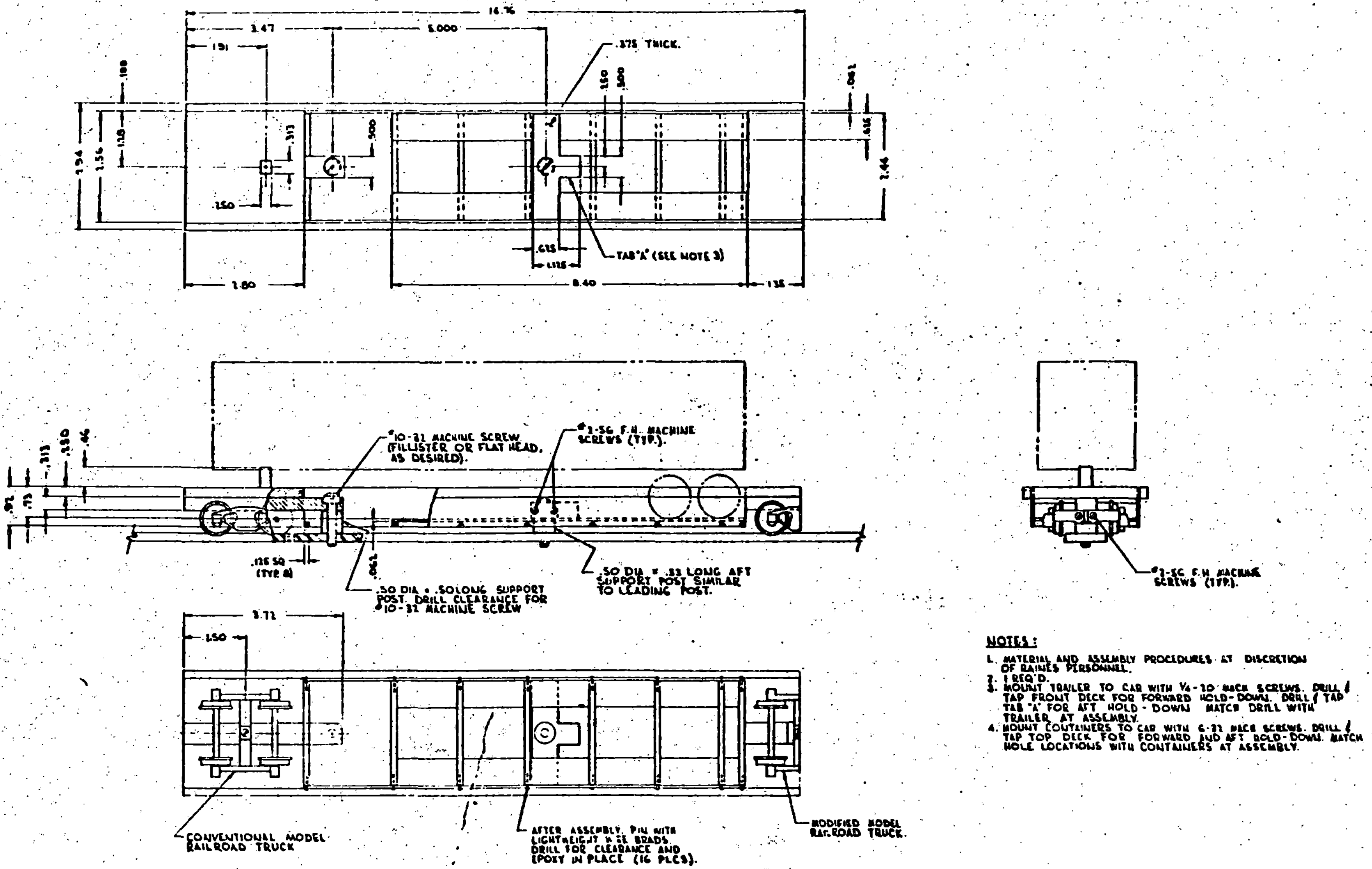


Figure 7a. Drawing of Model for Paton Lo Pro Car. Leading Unit. One Constructed.

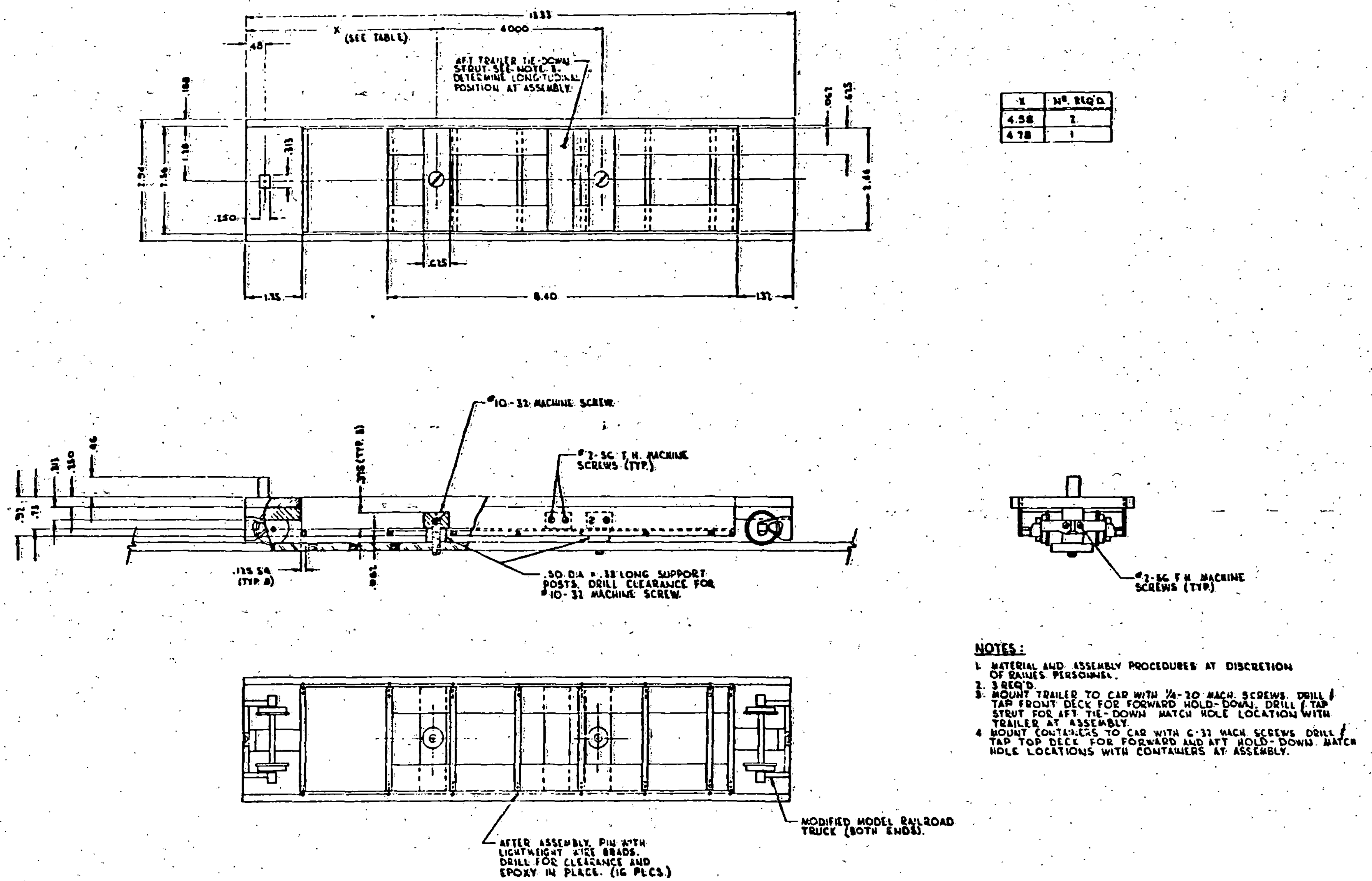


Figure 7b. Drawing of Model for Paton Lo Pro Car. Middle Unit. Three Constructed.

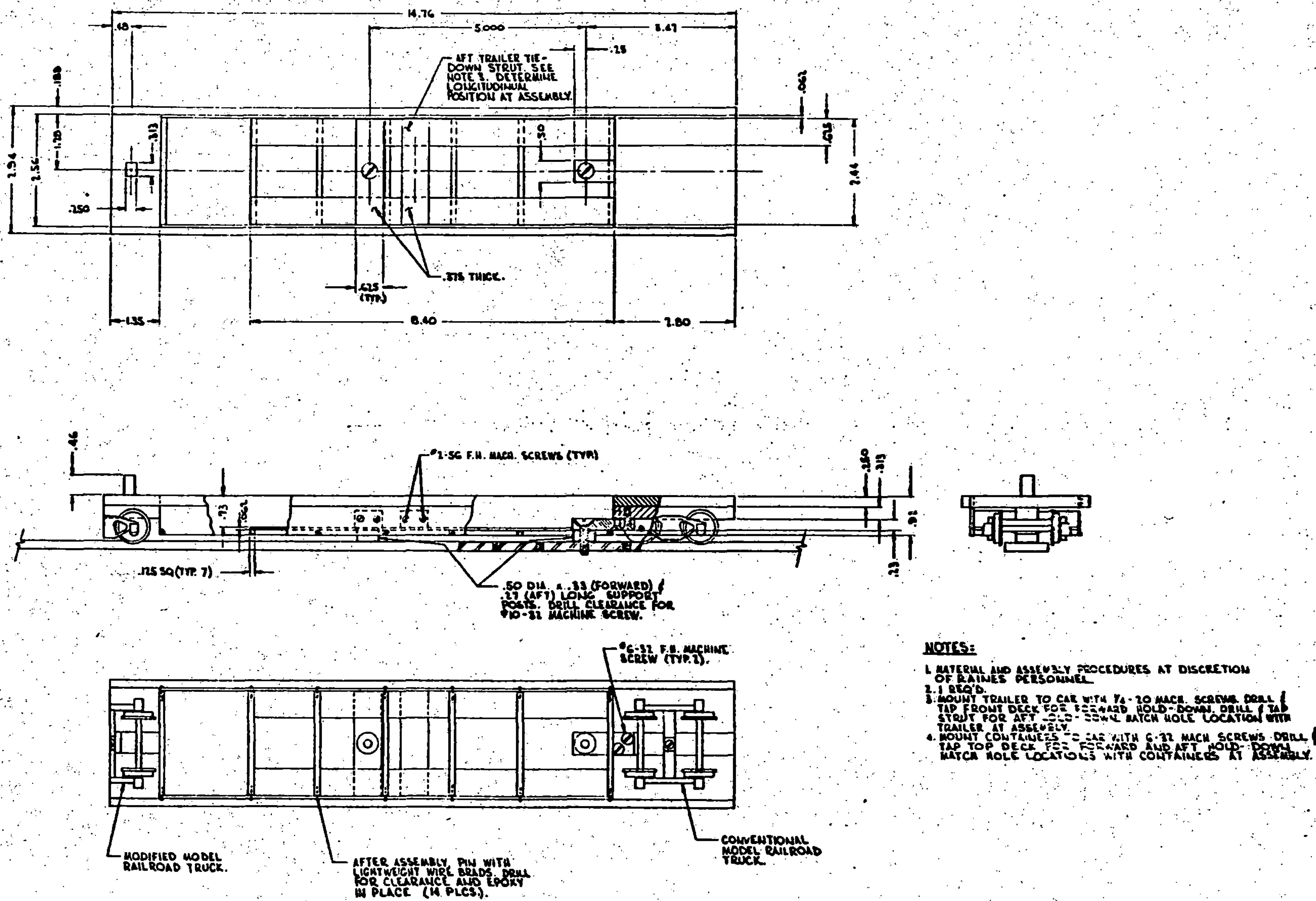


Figure 7c. Drawing for Model for Paton Lo Pro Car. Trailing Unit. One Constructed.

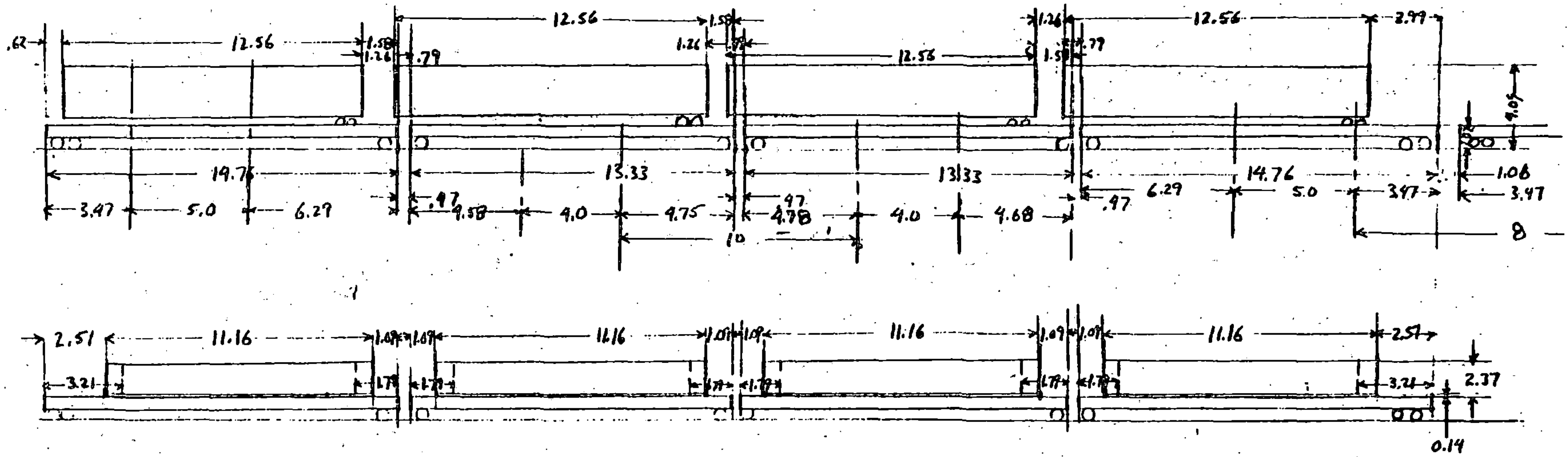
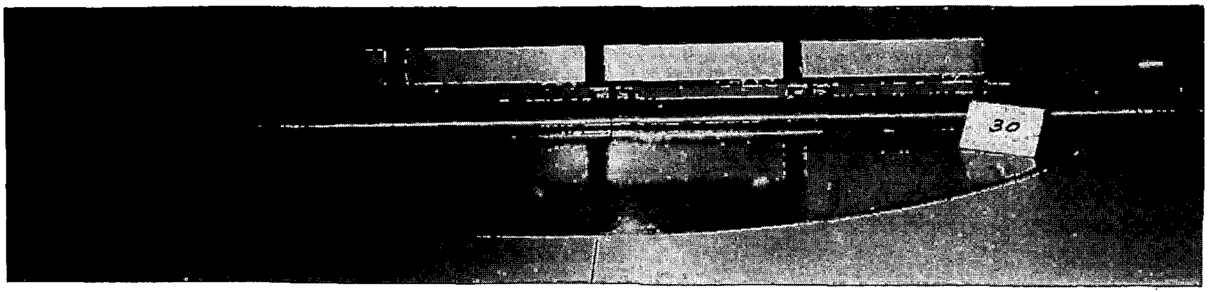
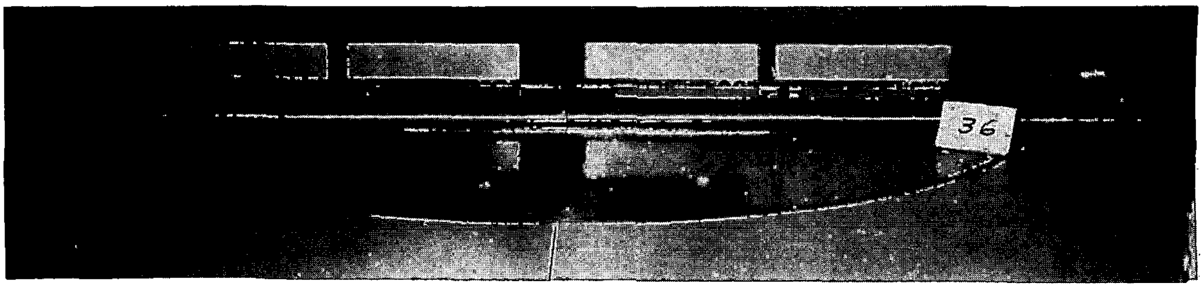


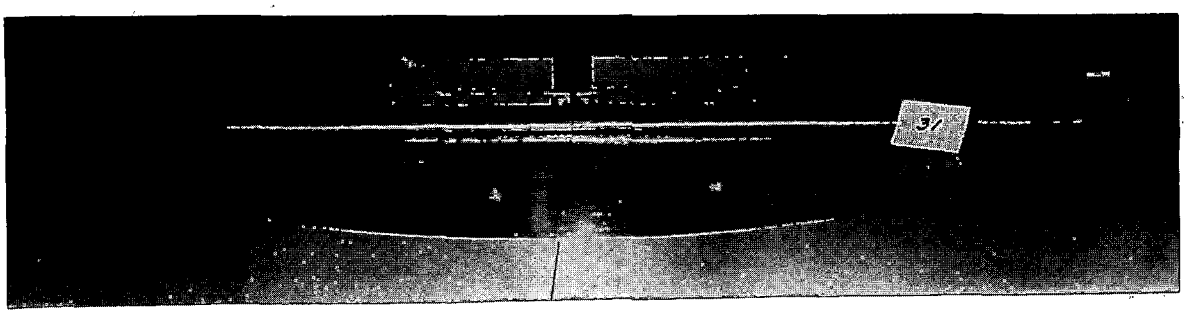
Figure 8. Location of Trailers and Containers on Paton Lo Pro Car and Between Units of Car as Mounted in the Wind Tunnel. Top - Trailers. Bottom - Containers.



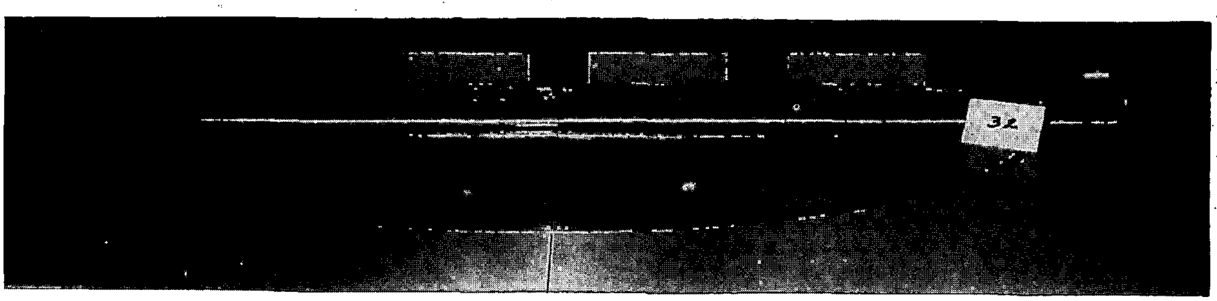
Two Middle Units on Balance, 45' Trailers



Trailing and Leading Units on Balance, 45' Trailers



Two Middle Units on Balance, 40' Containers



Two Middle Units on Balance, 35' Containers

Figure 9. Paton Lo Pro Model in Wind Tunnel.

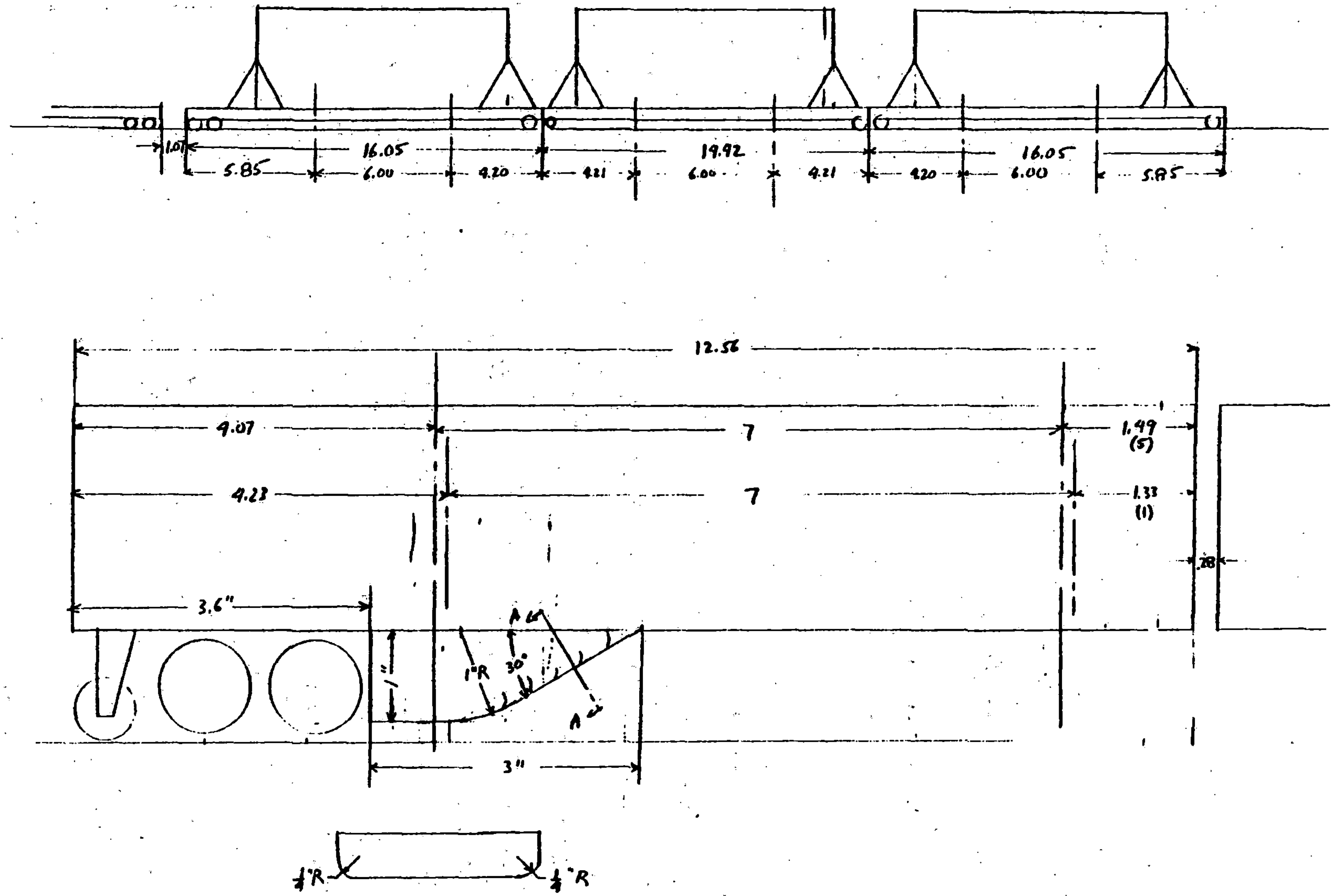
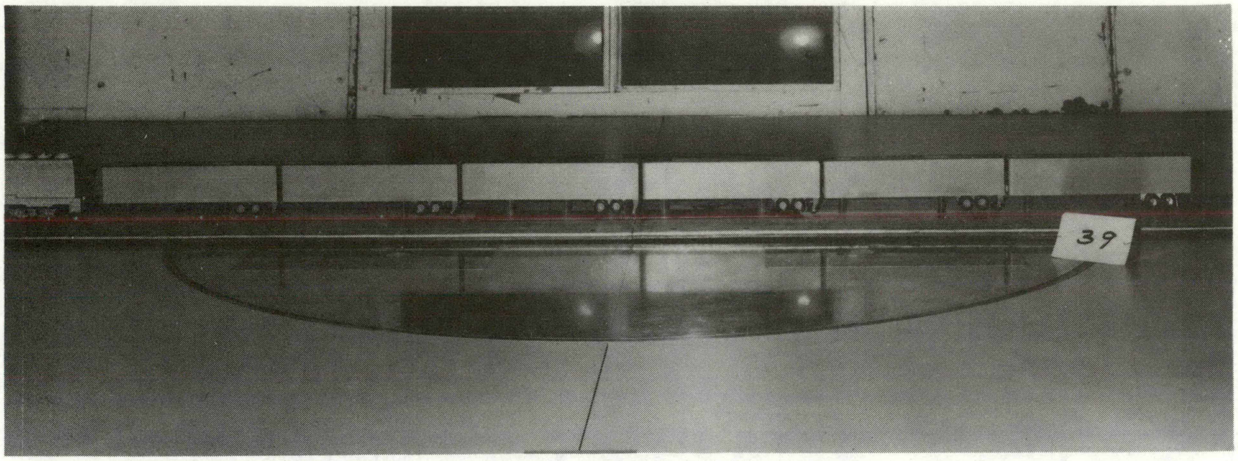
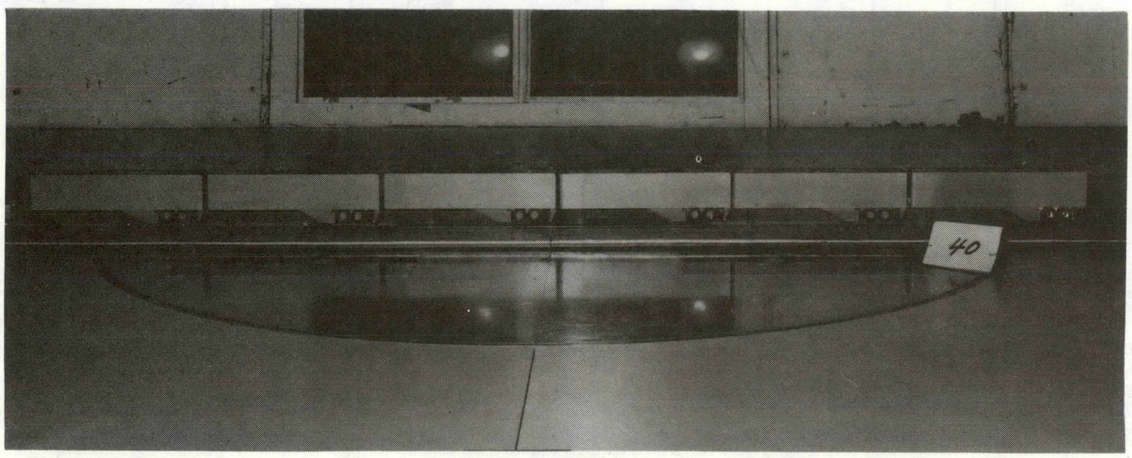


Figure 10. Top - Location Between Units of Southern Pacific Double Stack Articulated Container Car as Mounted in the Wind Tunnel. Bottom - Roadrailer Model as Mounted in the Wind Tunnel With Removable Skirt.



Standard Units



Units With Fairing Skirt

Figure 11. Roadrailer in Wind Tunnel.

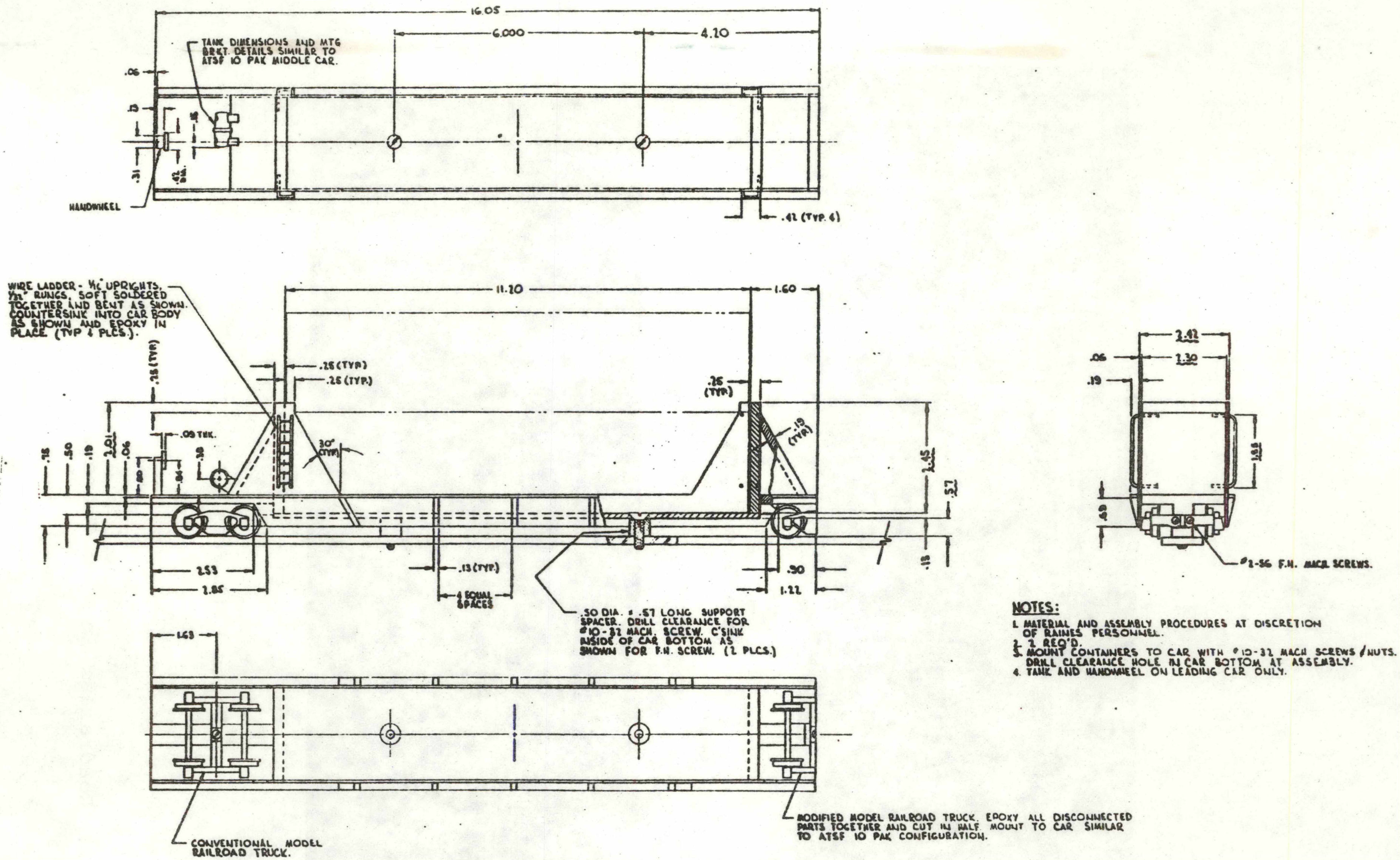


Figure 12a. Drawing of Model for Southern Pacific Double Stack Articulated Container Car. Leading and Trailing Unit. Two Constructed.

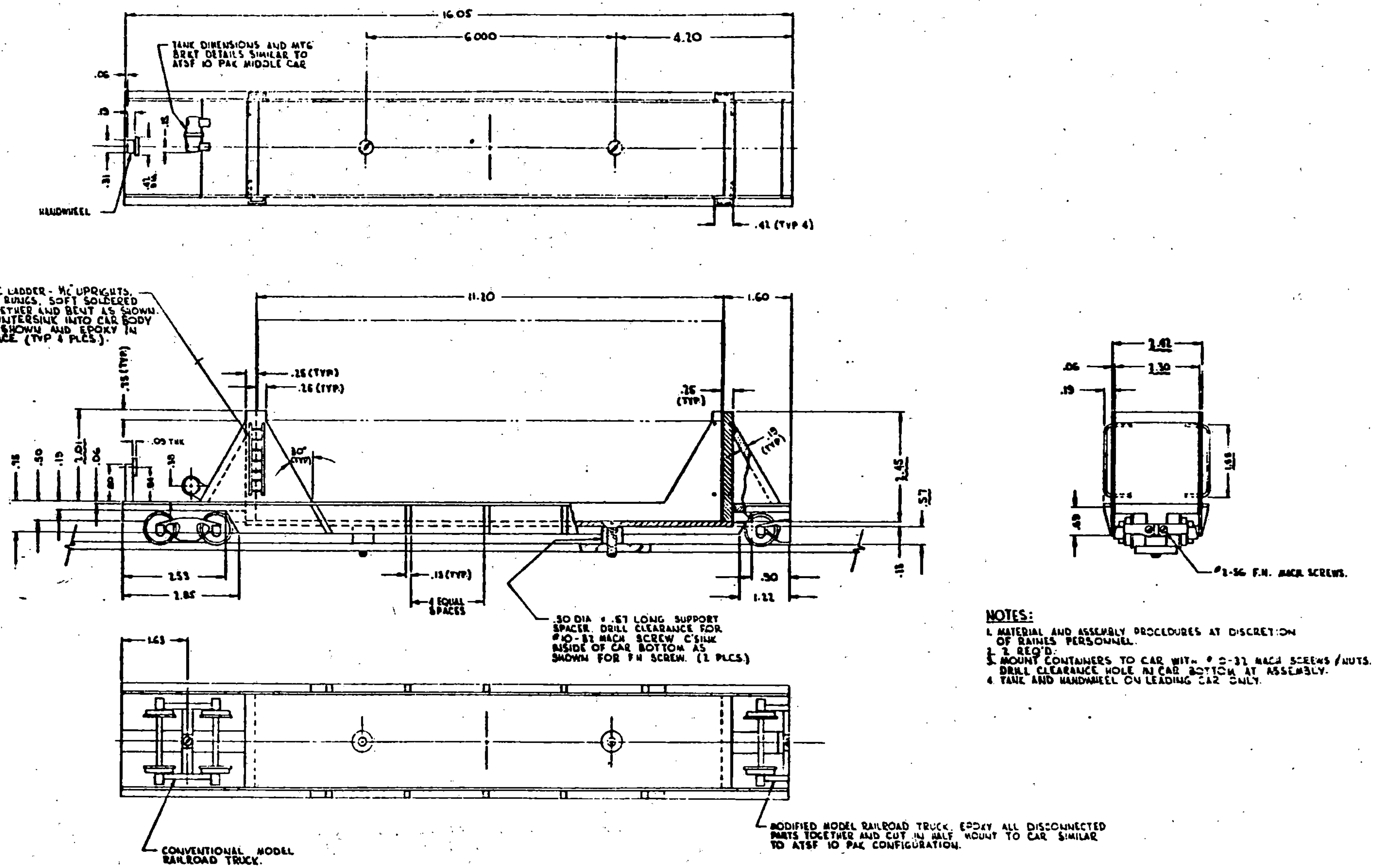
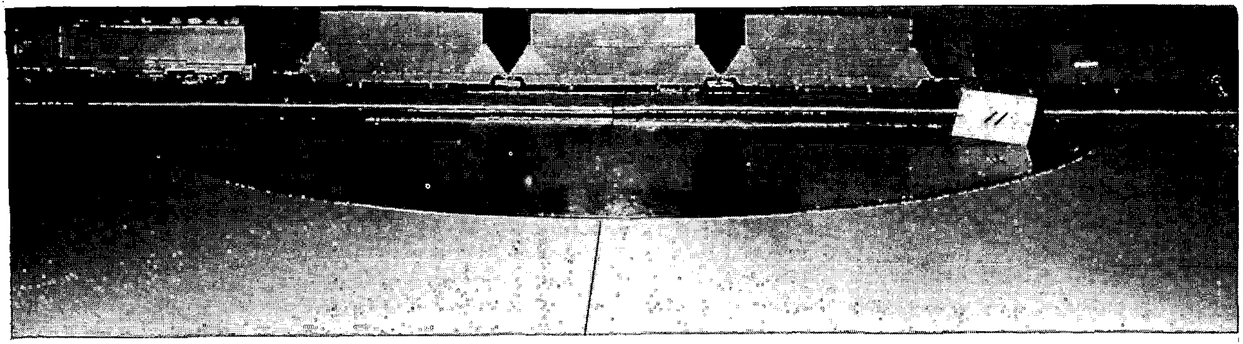
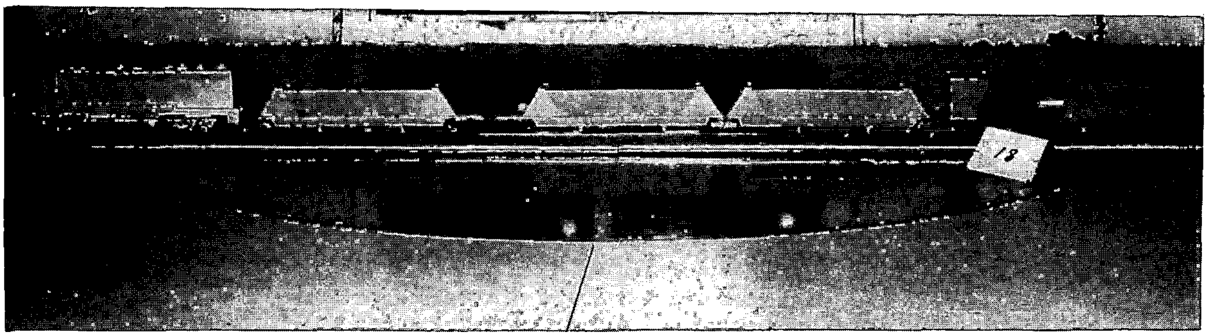


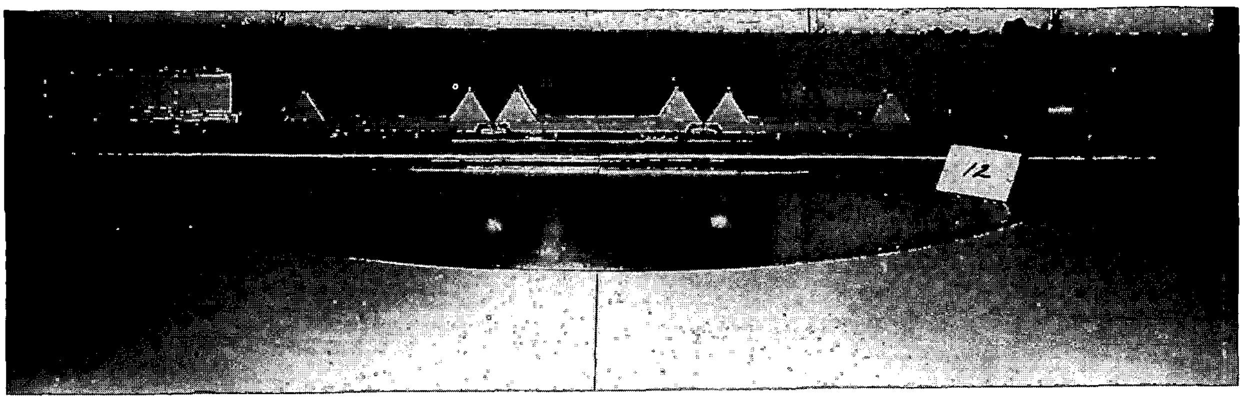
Figure 12b. Drawing of Model for Southern Pacific Double Stack Articulated Container Car. Middle Unit. One Constructed.



Middle Unit on Balance, Two 40' Containers

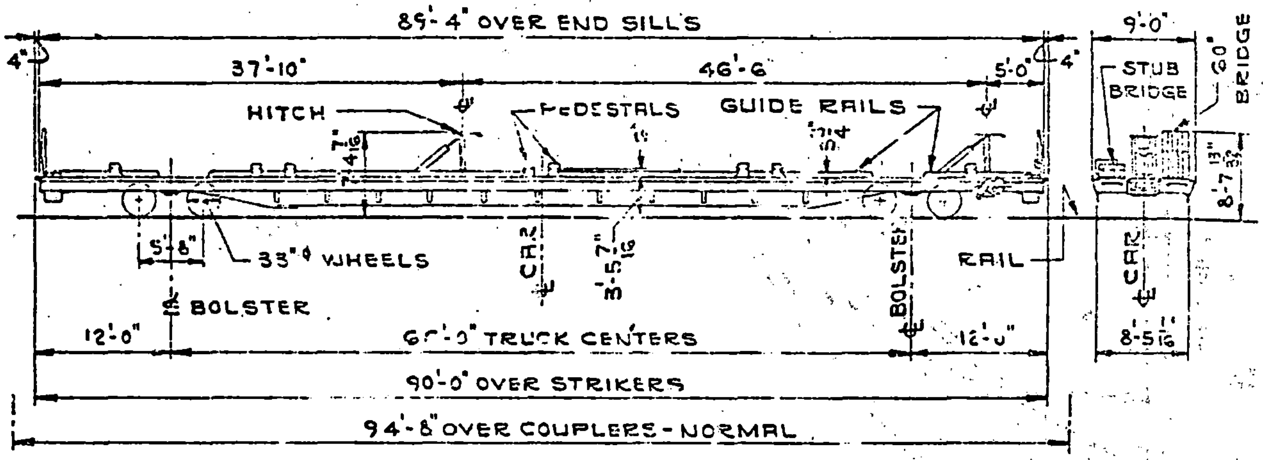


Leading Unit on Balance, One 40' Container



Middle Unit on Balance, Empty

Figure 13. Southern Pacific Double Stack Articulated Container Car in Wind Tunnel.



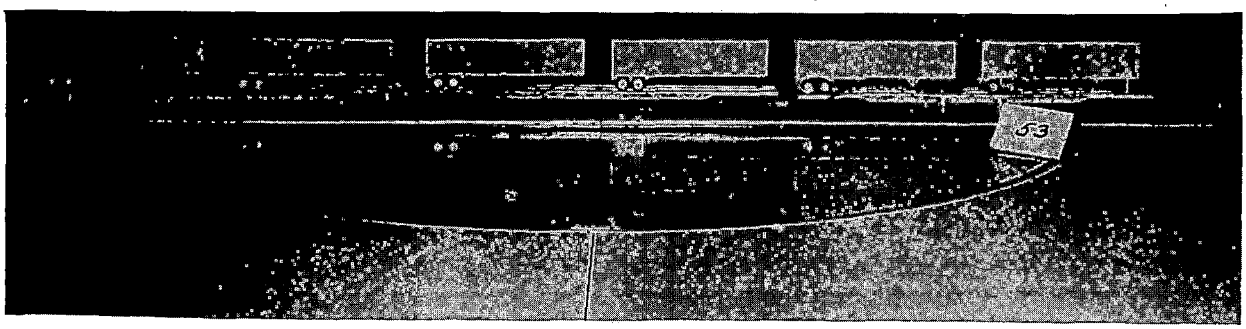


Figure 14. Top - Drawing of TTX Car. Bottom - TTX Car in the Wind Tunnel.

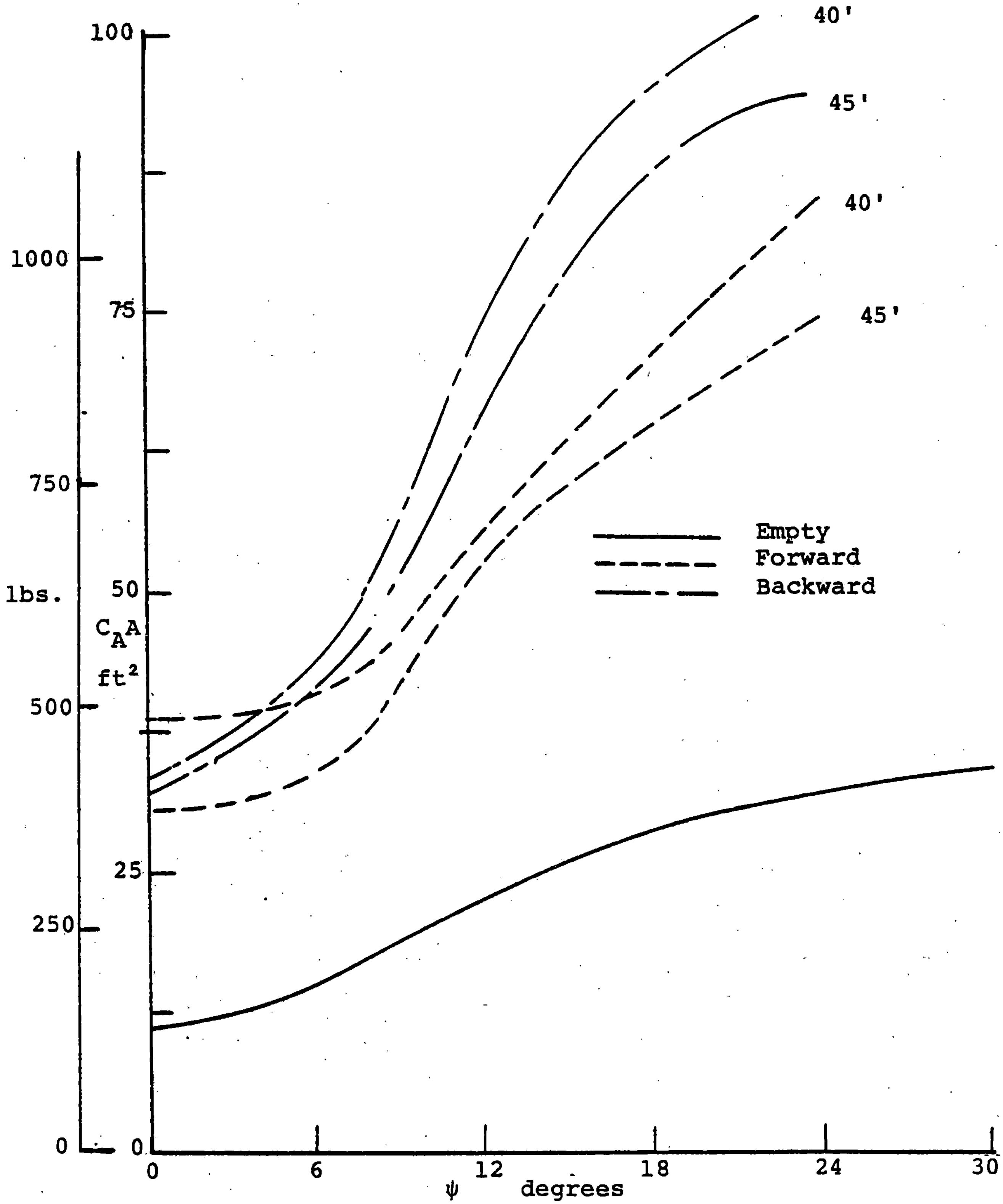


Figure 15. Axial Force Per Unit of Trailer Train Prototype as a Function of Yaw Angle. Forces Given as a Force Area and for 70 mph Relative Wind Velocity.

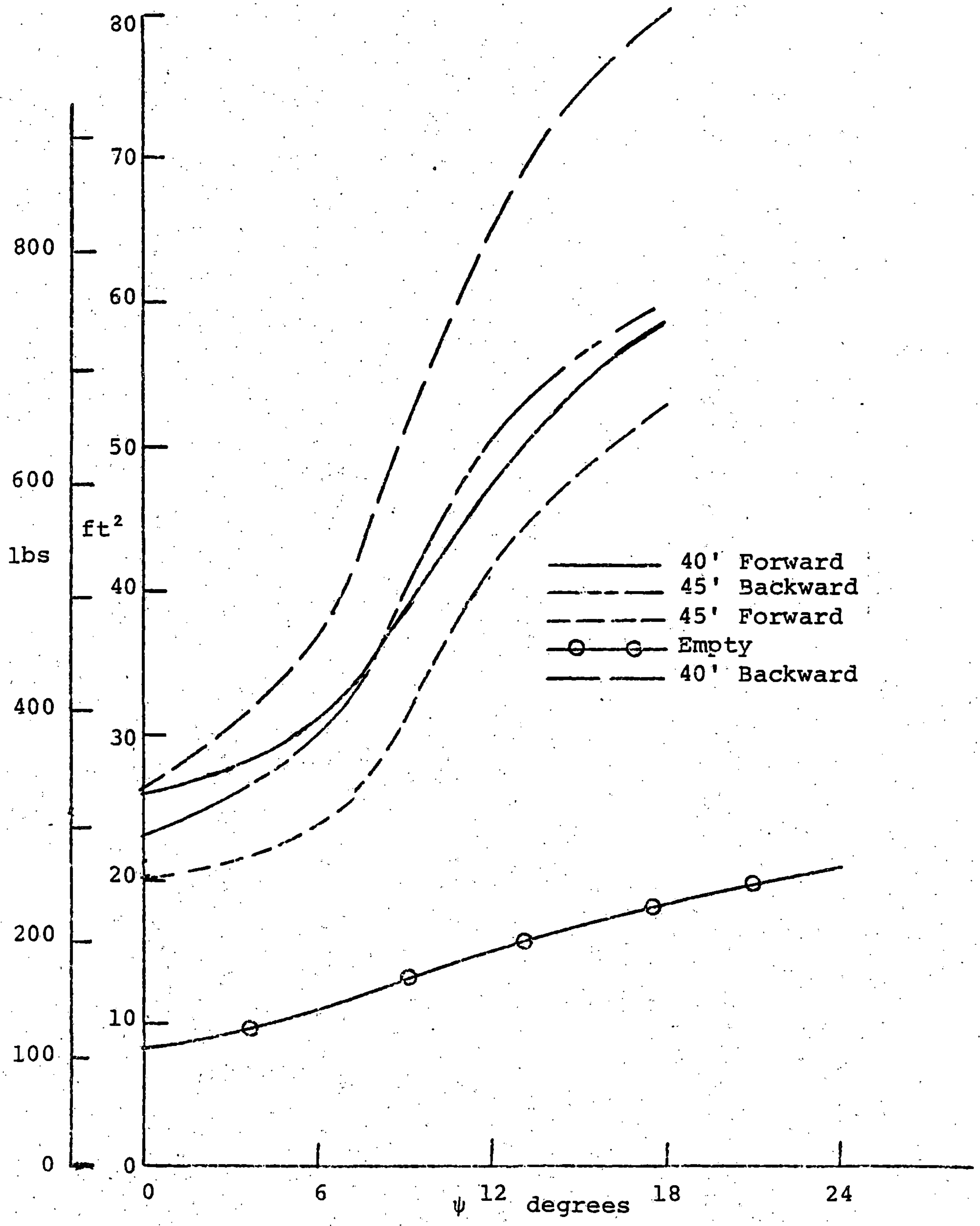


Figure 16. Axial Force per Unit on Santa Fe 10 Pac as a Function of Yaw Angle. Force Given as a Force Area and for 70 mph Relative Wind Velocity.

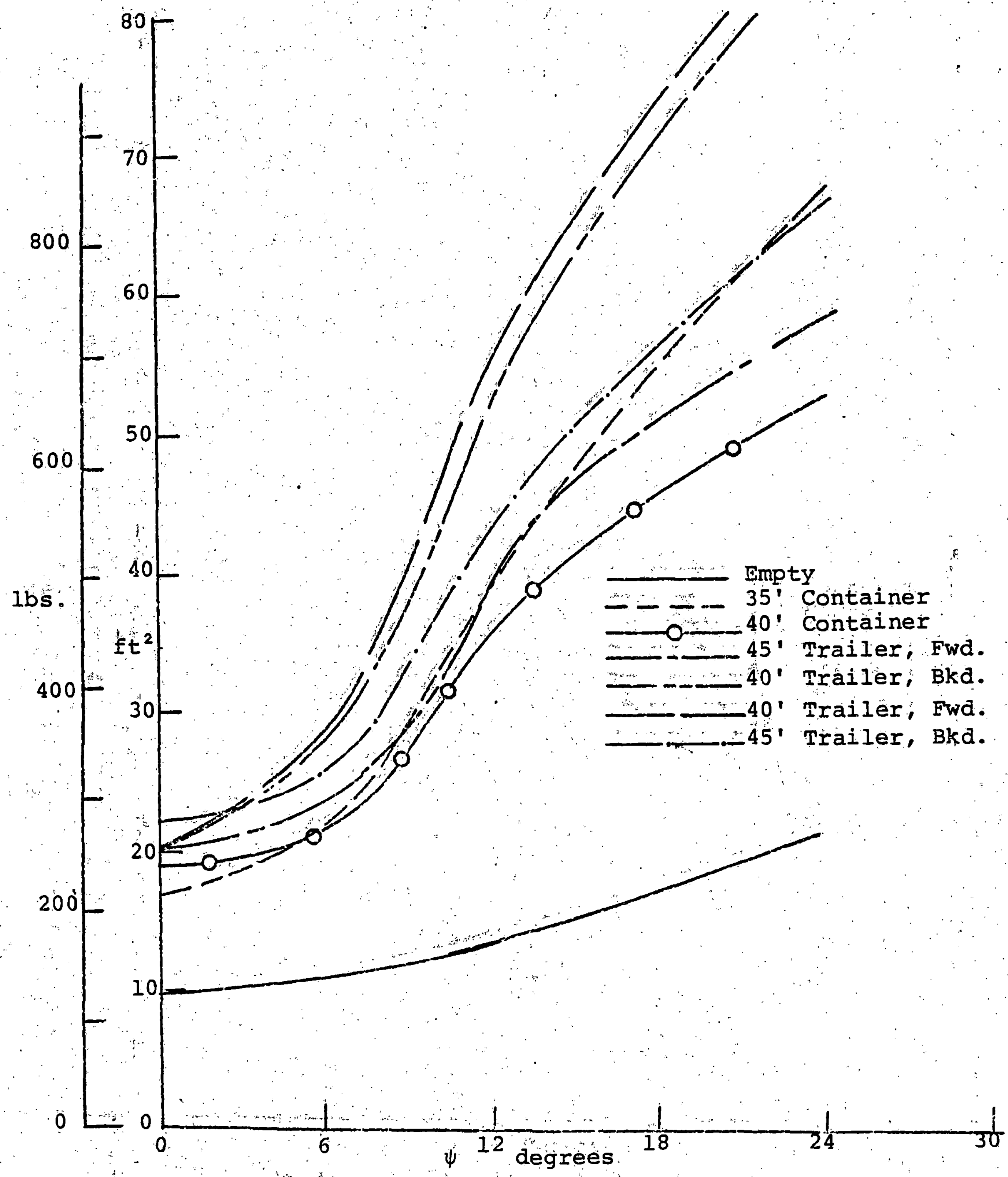


Figure 17. Axial Force per Unit on Paton Lo Pro as Function of Yaw Angle. Force Given as a Force Area and for 70 mph Relative Wind Velocity.

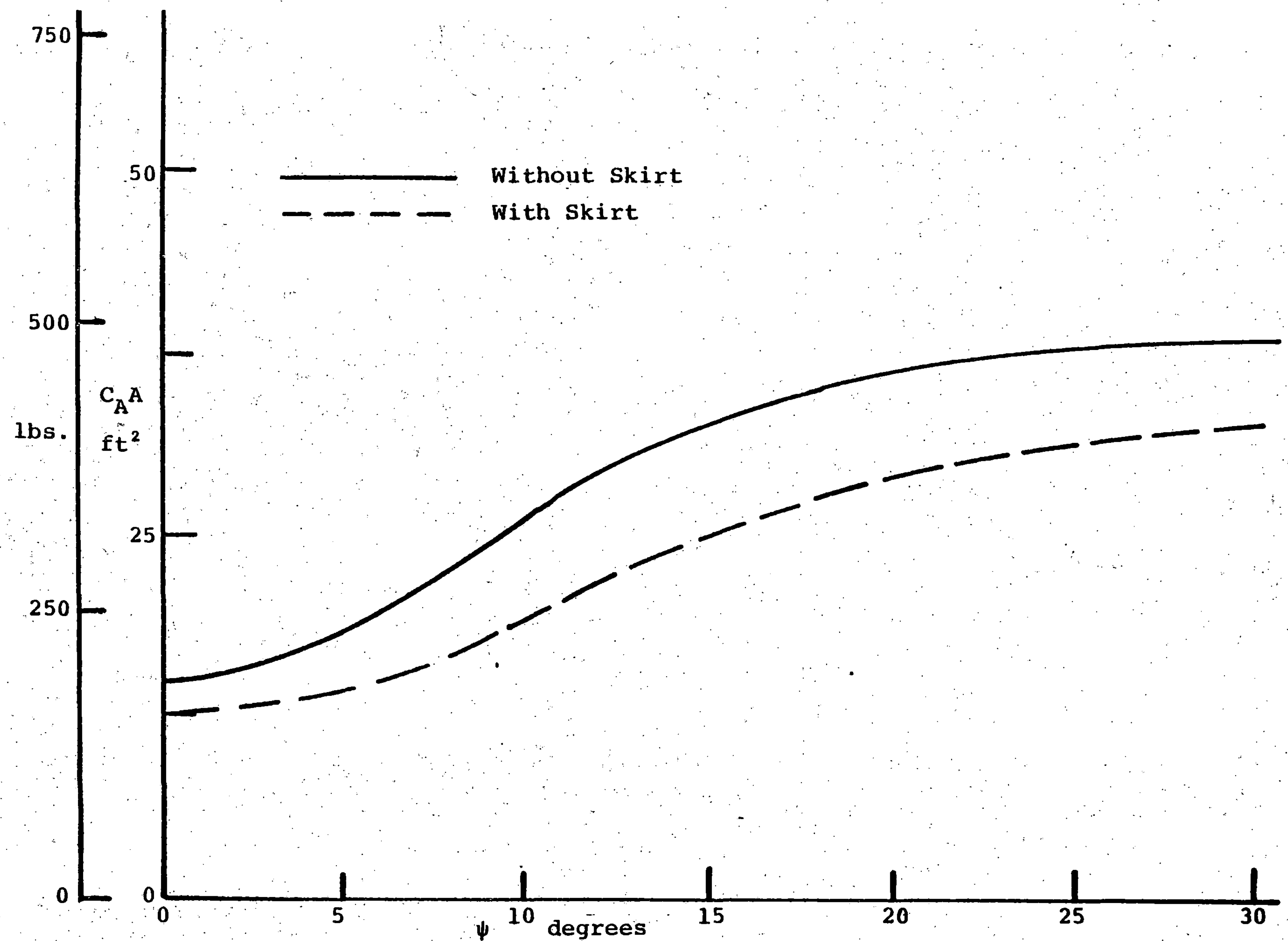


Figure 18. Axial Force Per Unit of Roadrailer as a Function of Yaw Angle. Forces Given as a Force Area and for 70 mph Relative Wind Velocity.

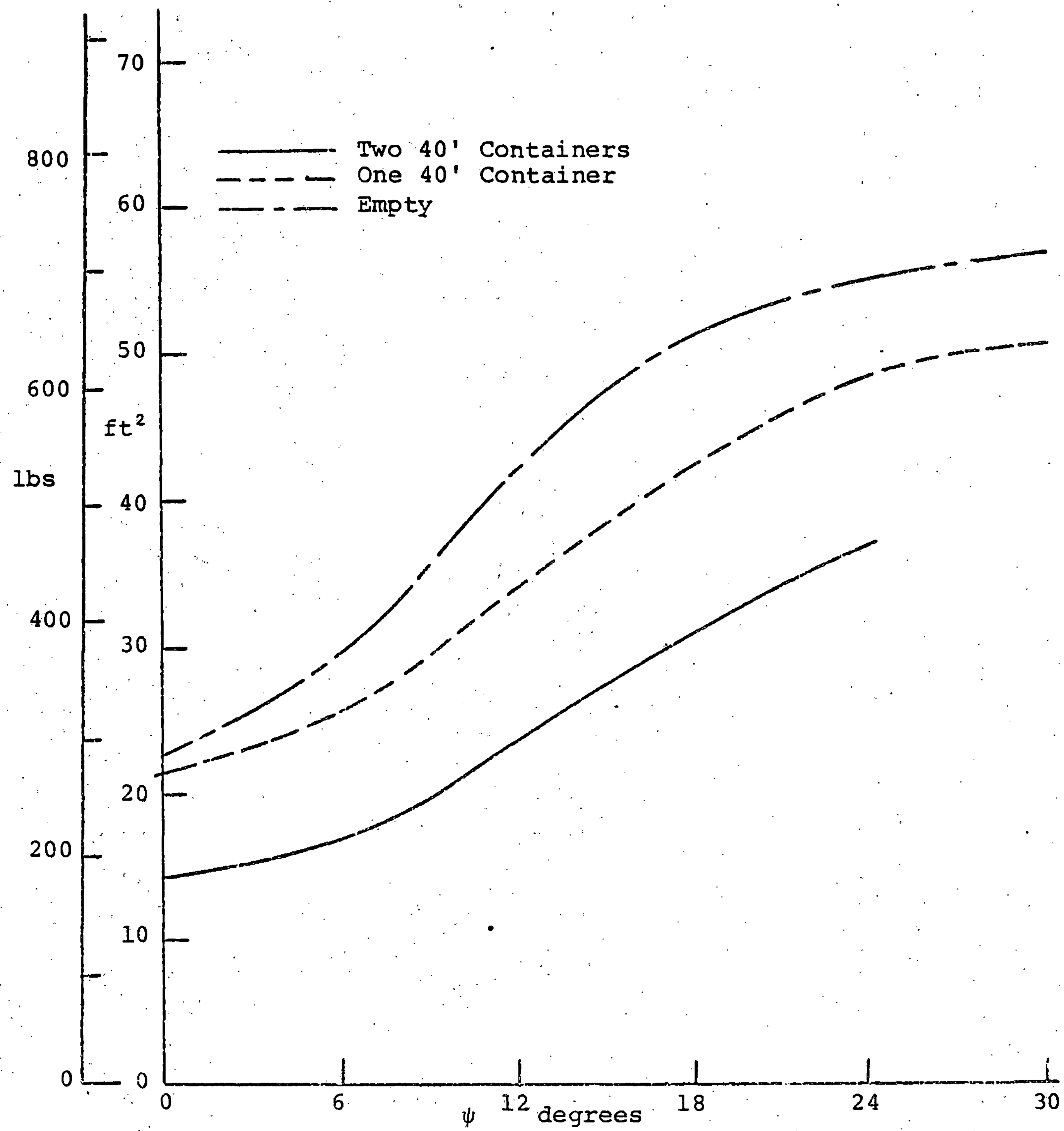


Figure 19. Axial Force on the Southern Pacific Double Stack Articulated Container Car as a Function of Yaw Angle. Forces are Per Container and Per Car Unit for the Empty Case. Force Given as a Force Area and for 70 mph Relative Wind Velocity.

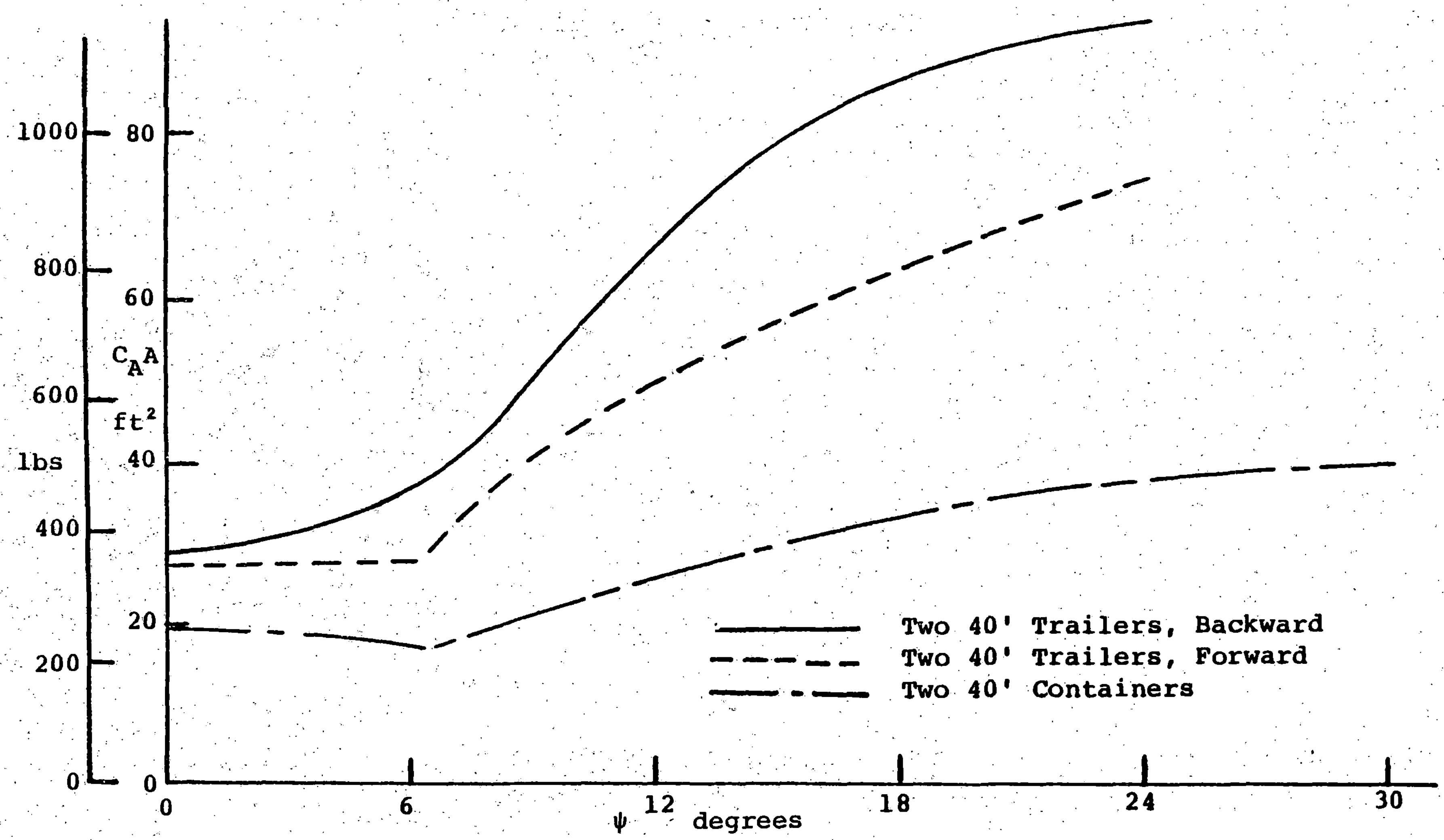


Figure 20. Axial Force on TTX Car per Trailer or Container as a Function of Yaw Angle. Force Given as a Force Area and for 70 mph Relative Wind Velocity.

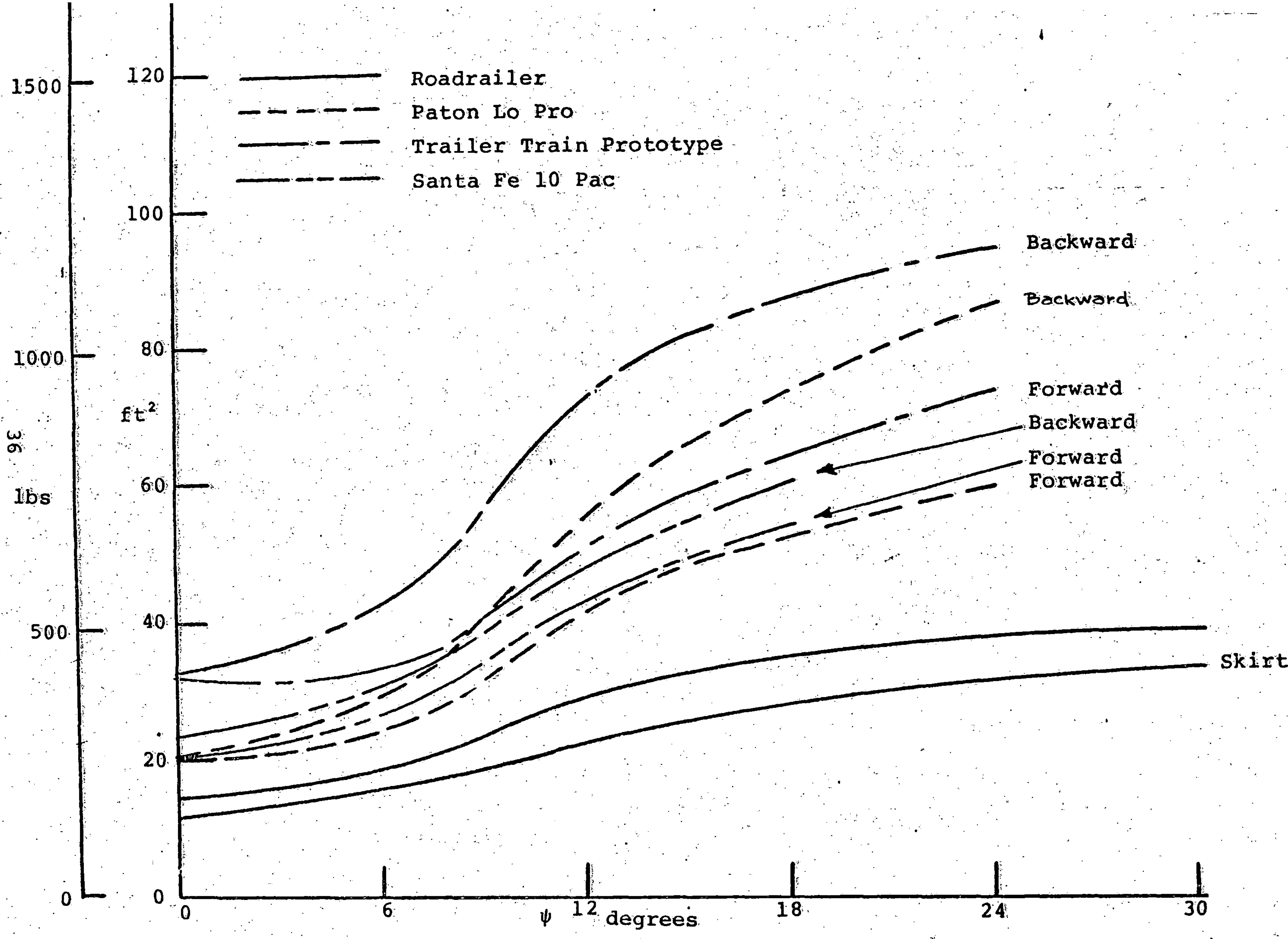


Figure 21. Axial Force on Different Cars with 45 Foot Trailers per Trailer as a Function of Yaw Angle. Force Given as a Force Area and for 70 mph Relative Wind Velocity.

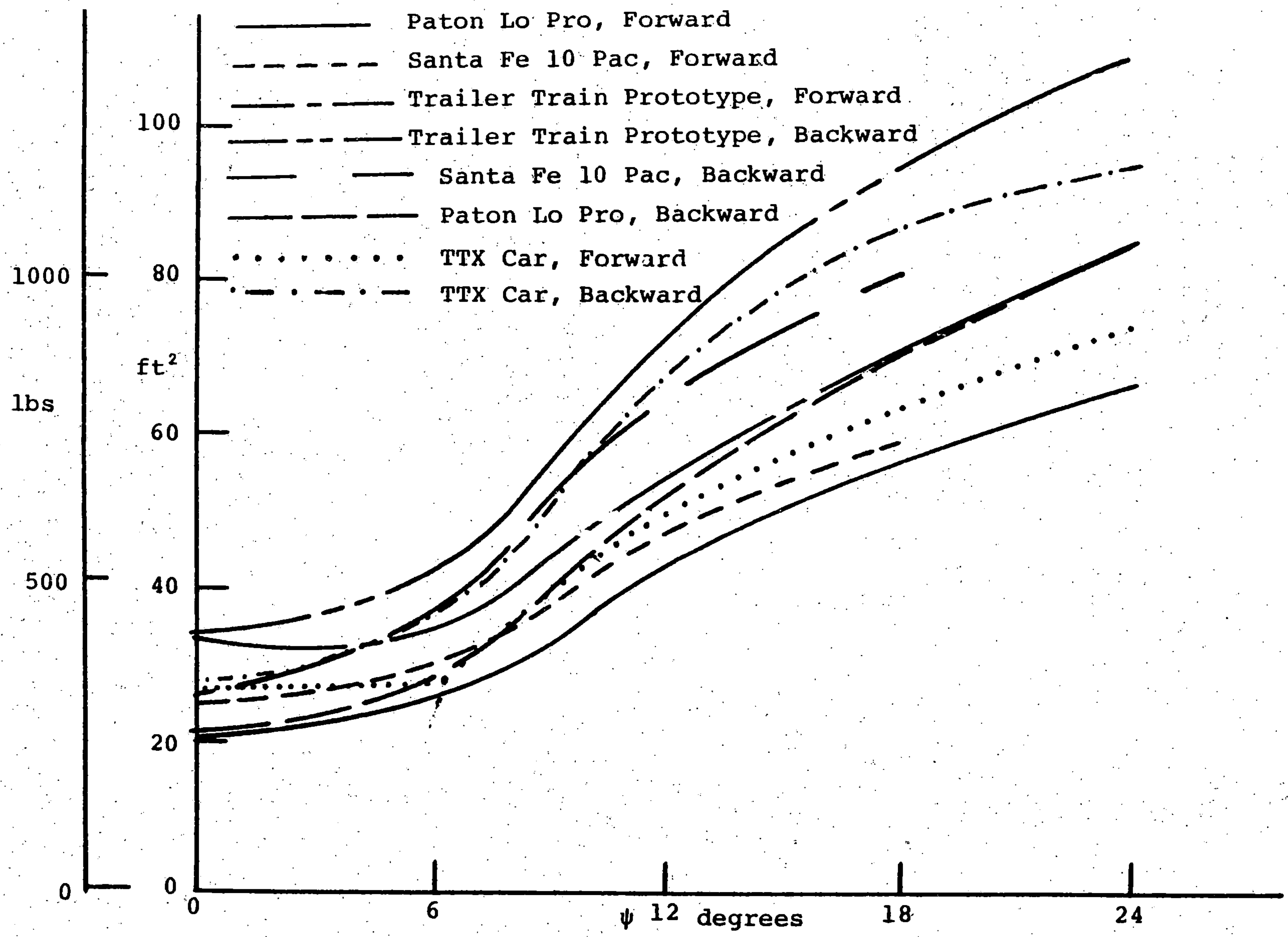


Figure 22. Axial Force on Different Cars with 40 Foot Trailers per Trailer as a Function of Yaw Angle. Force Given as a Force Area and for 70 mph Relative Wind Velocity.

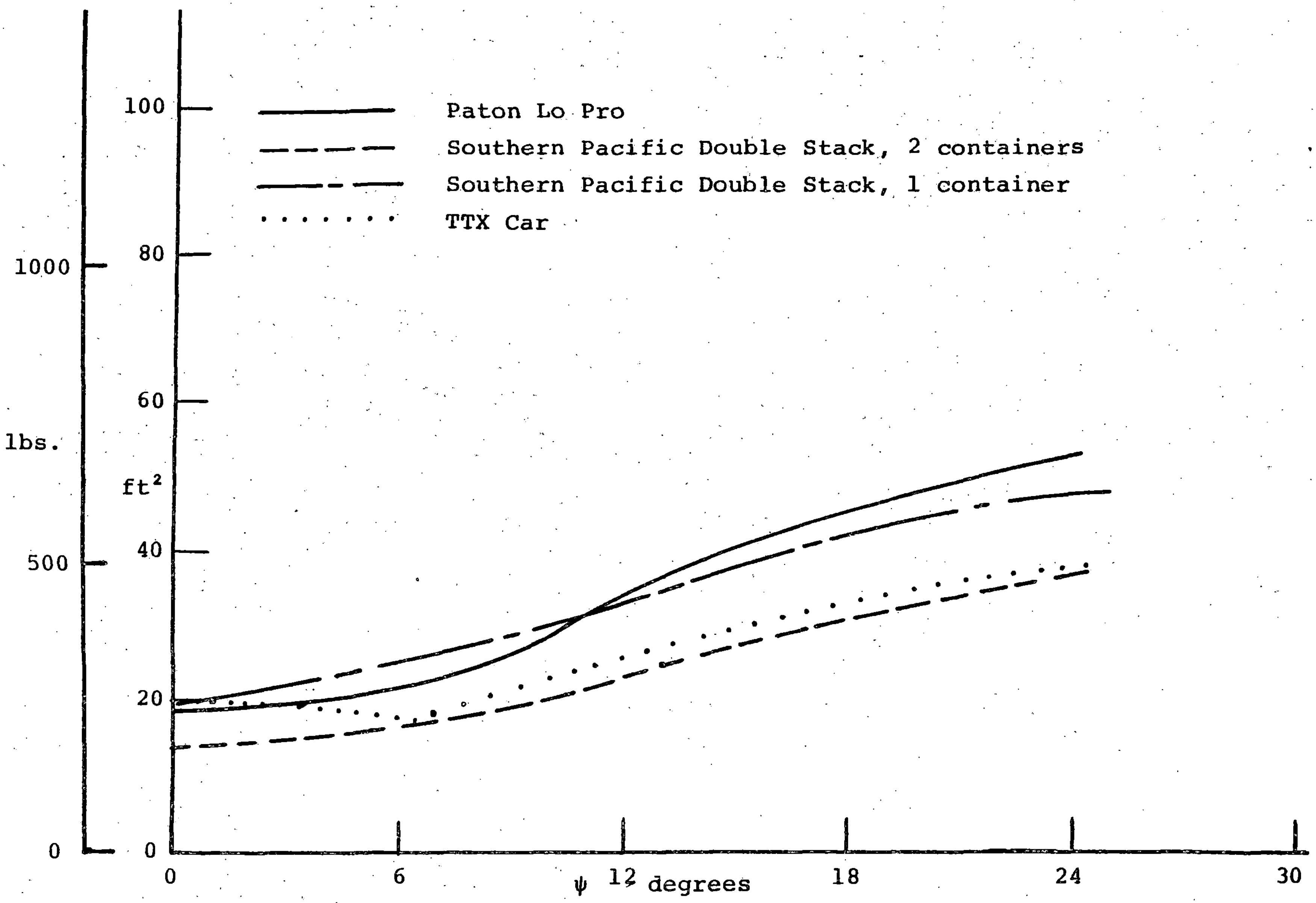


Figure 23. Axial Force on Different Cars with 40 Foot Containers per Container as a Function of Yaw Angle. Force Given as a Force Area and for 70 mph Relative Wind Velocity.

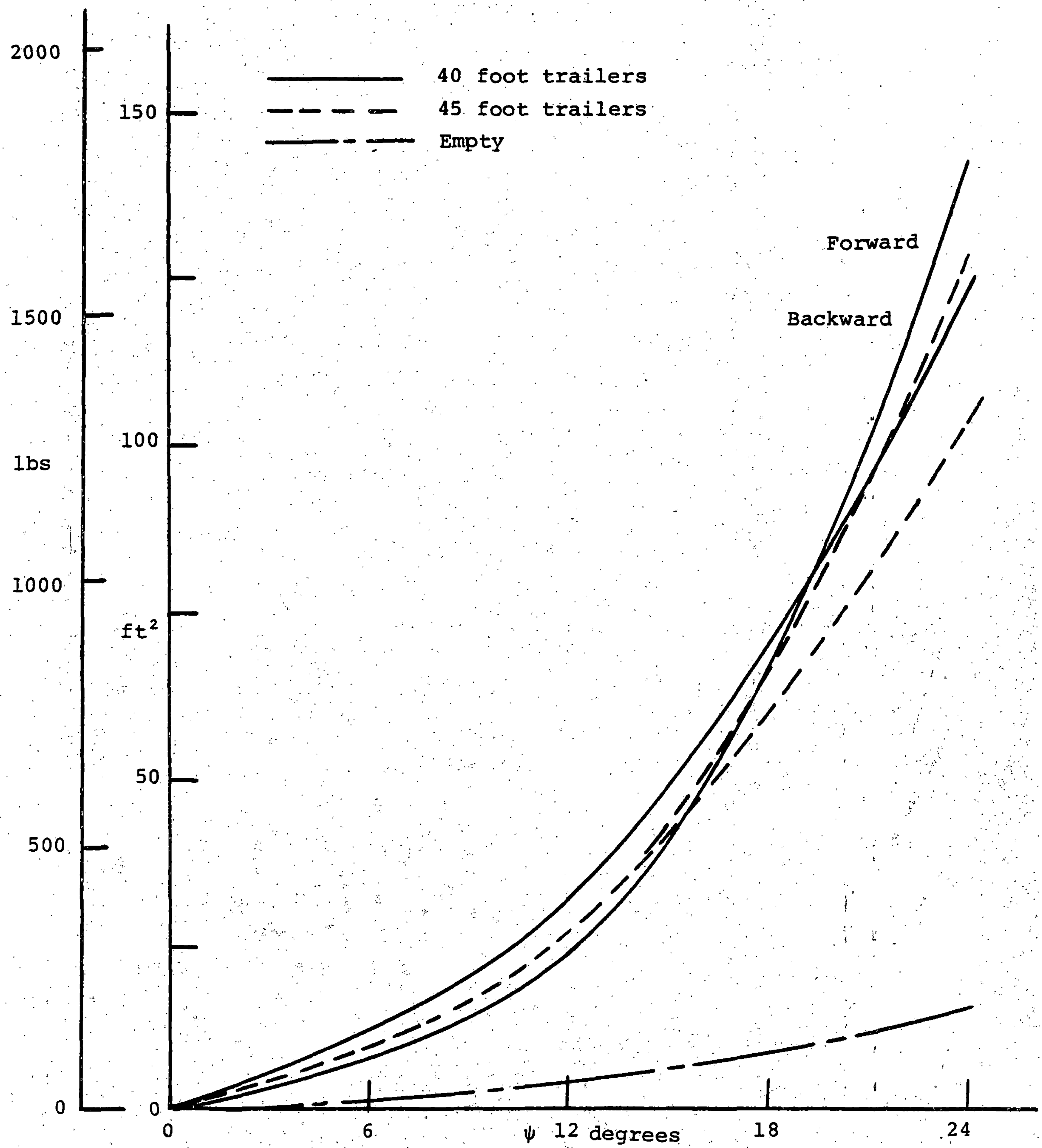


Figure 24. Lift Force on One Unit of Trailer Train Prototype as a Function of Yaw Angle for Different Loading Conditions. Force Given as a Force Area and for 70 mph Relative Wind Velocity.

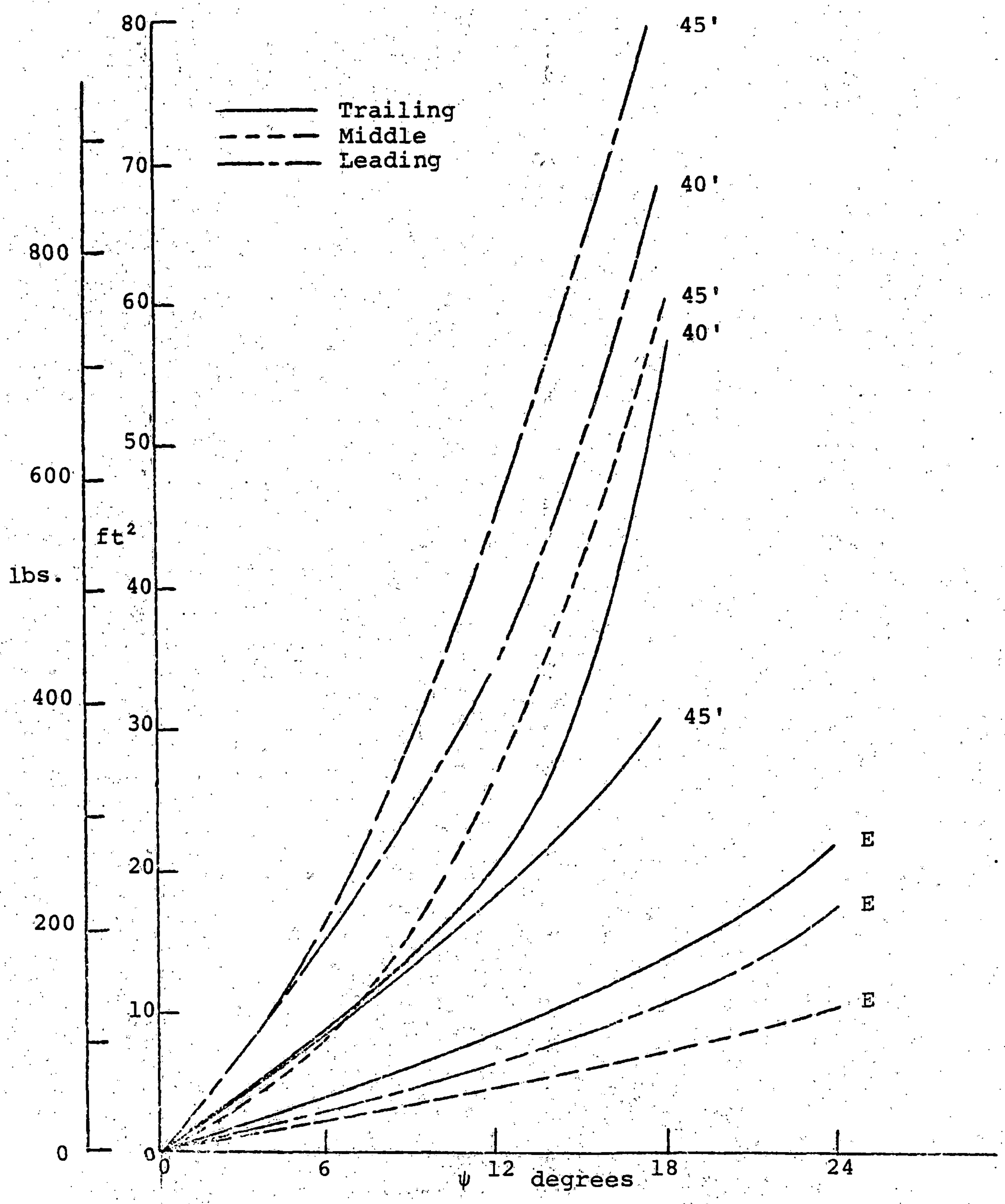


Figure 25a. Lift Force Per Unit on Santa Fe 10 Pac as a Function of Yaw Angle for Forward Direction. Force Given as a Force Area and for 70 mph Relative Wind Velocity.

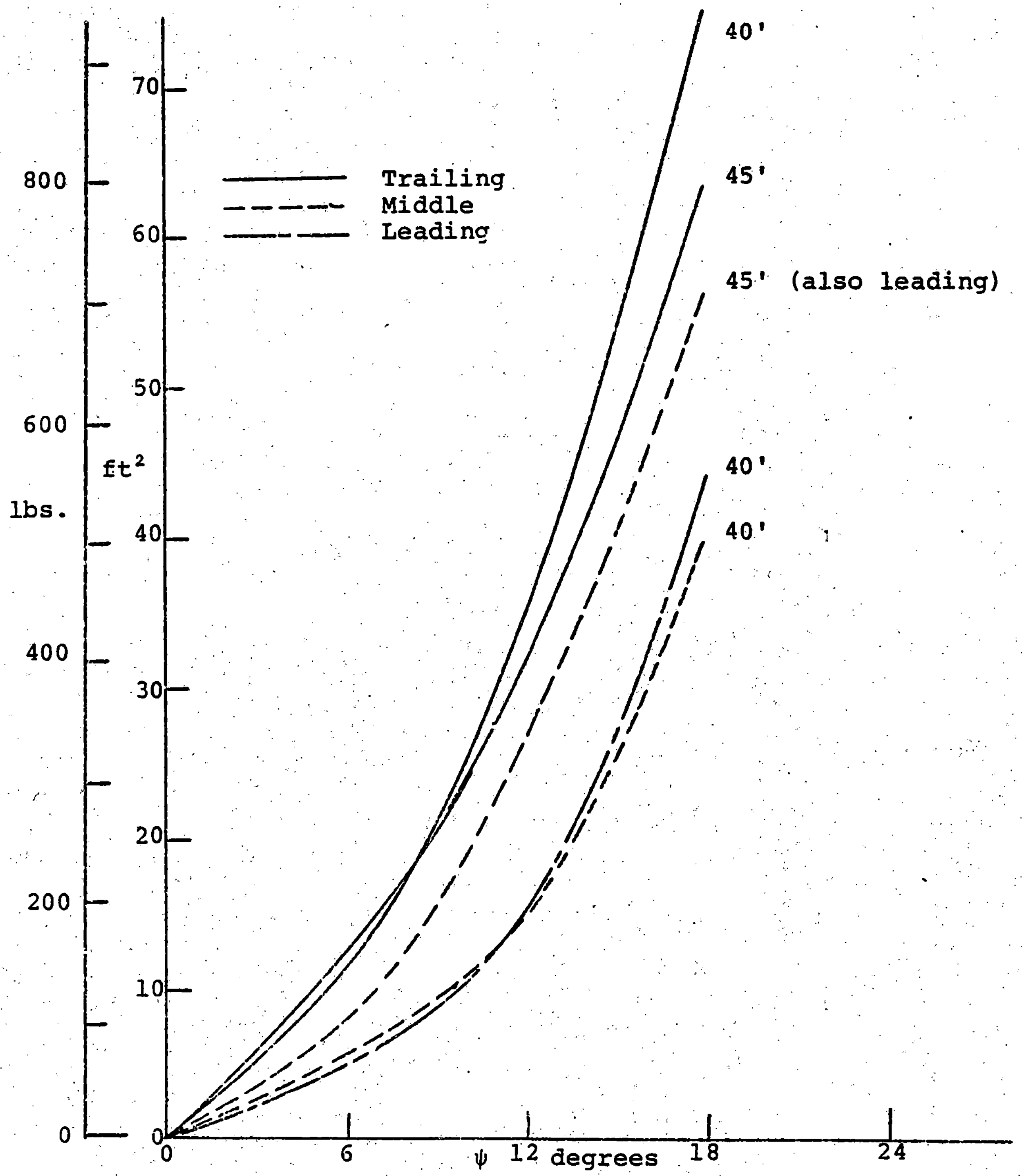


Figure 25b. Lift Force Per Unit on Santa Fe 10 Pac as a Function of Yaw Angle for Backwards Direction. Force Given as a Force Area and for 70 mph Relative Wind Velocity.

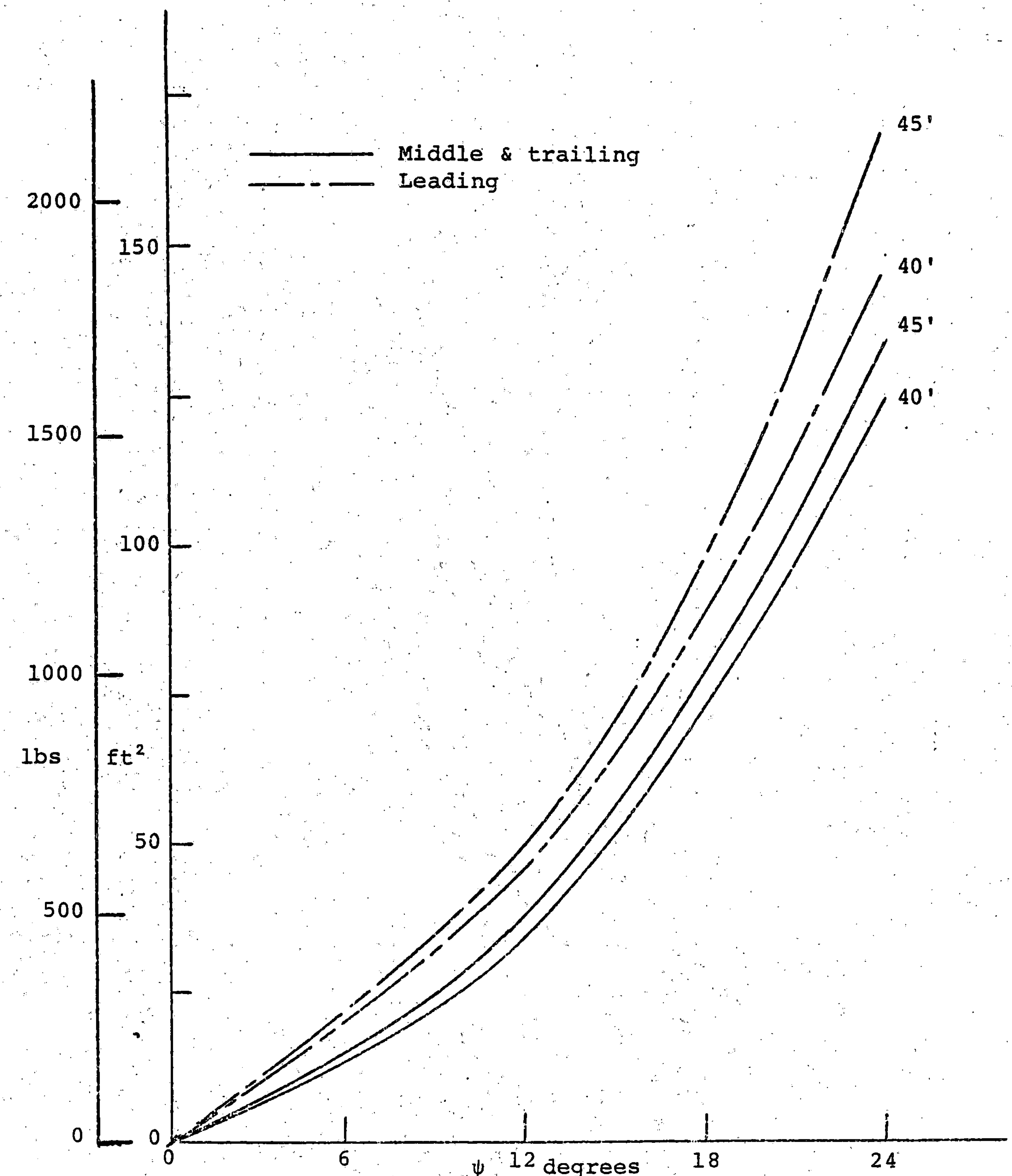


Figure 26a. Lift Force on Paton Lo Pro Units with 45 and 40 Foot Trailers Facing Forward as a Function of Yaw Angle. Lift Force is Given as a Force Area and for 70 mph Relative Wind Velocity.

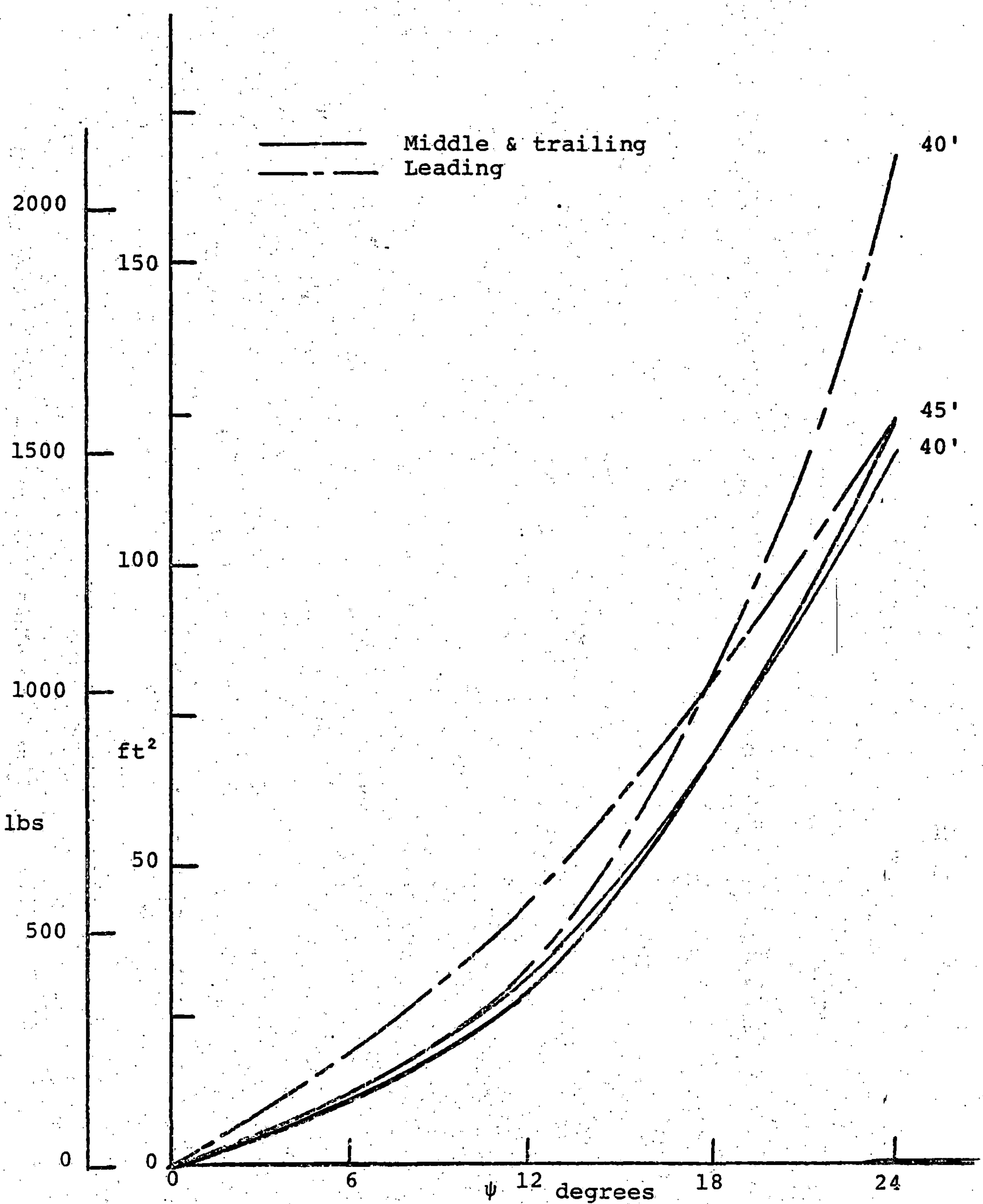


Figure 26b. Lift Force on Paton Lo Pro Units with 45 and 40 Foot Trailers Facing Backward as a Function of Yaw Angle. Lift Force is Given as a Force Area and for 70 mph Relative Wind Velocity.

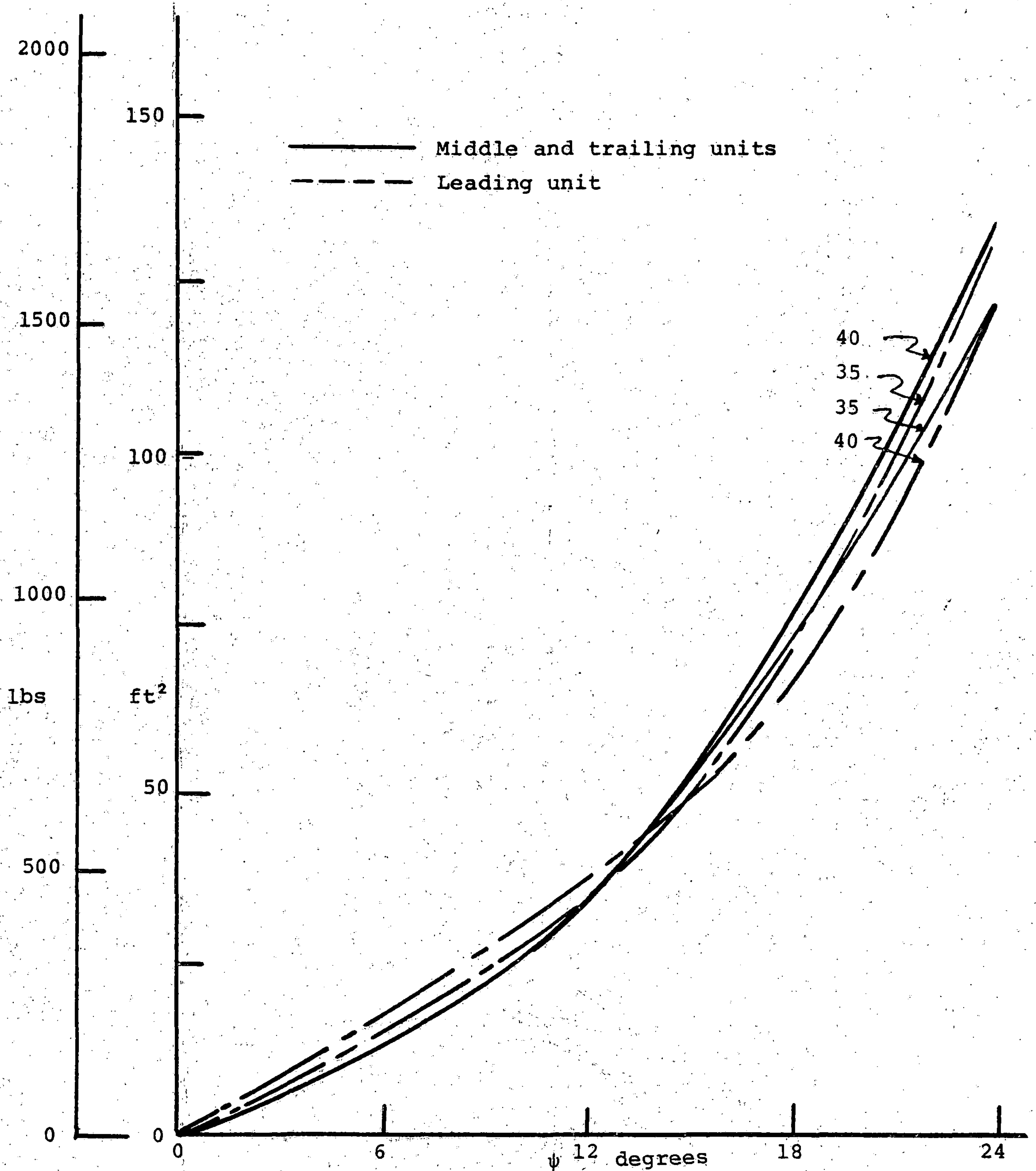


Figure 26c. Lift Force on Paton Lo Pro Units with 40 and 35 Foot Containers. Lift Force is Given as a Force Area and for 70 mph Relative Wind Velocity.

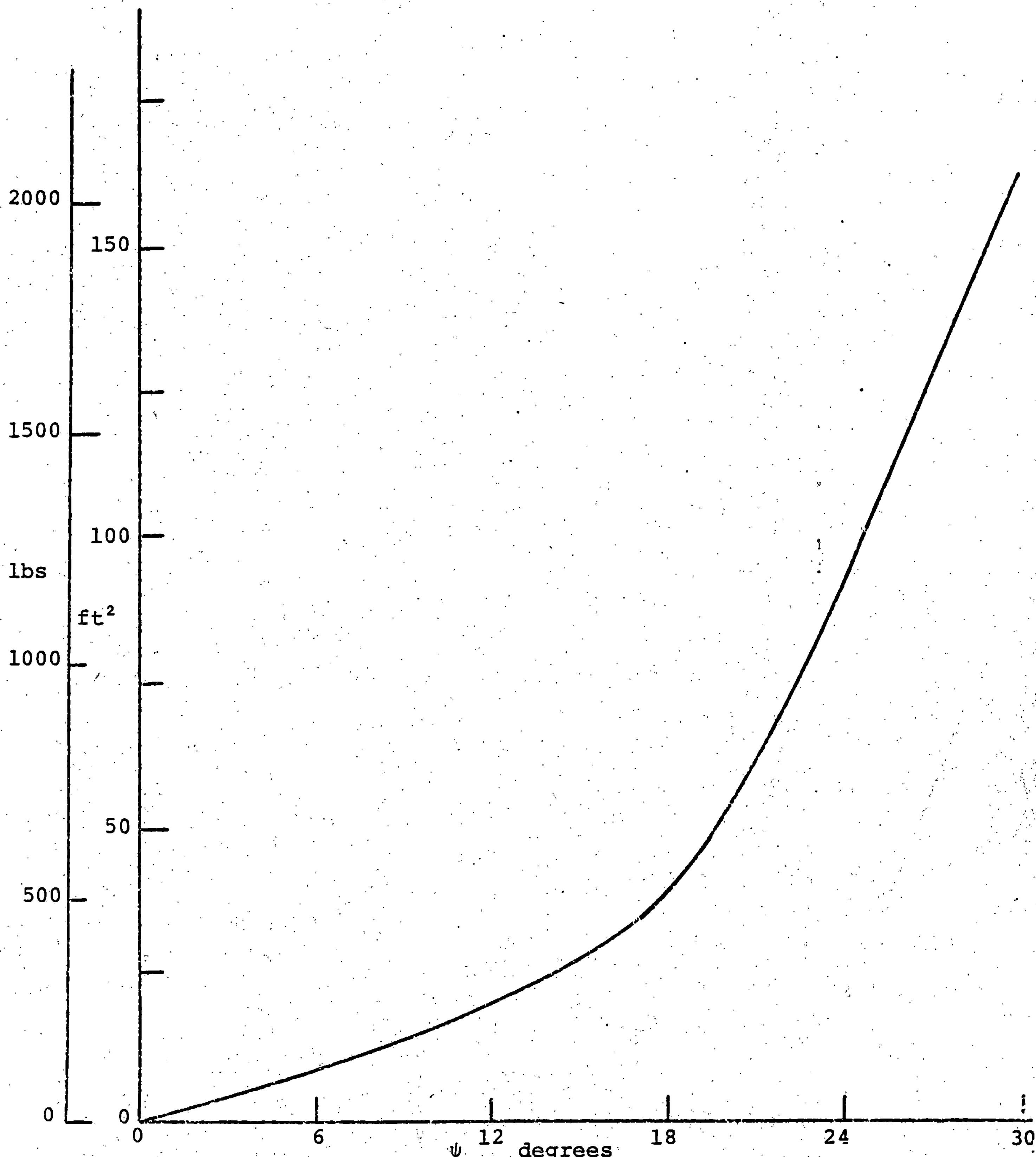


Figure 27. Lift Force Per Unit of Roadrailer as a Function of Yaw Angle. Result is Both for Normal Configuration and One with Skirt. Force Given as a Force Area and for 70 mph Relative Wind Velocity.

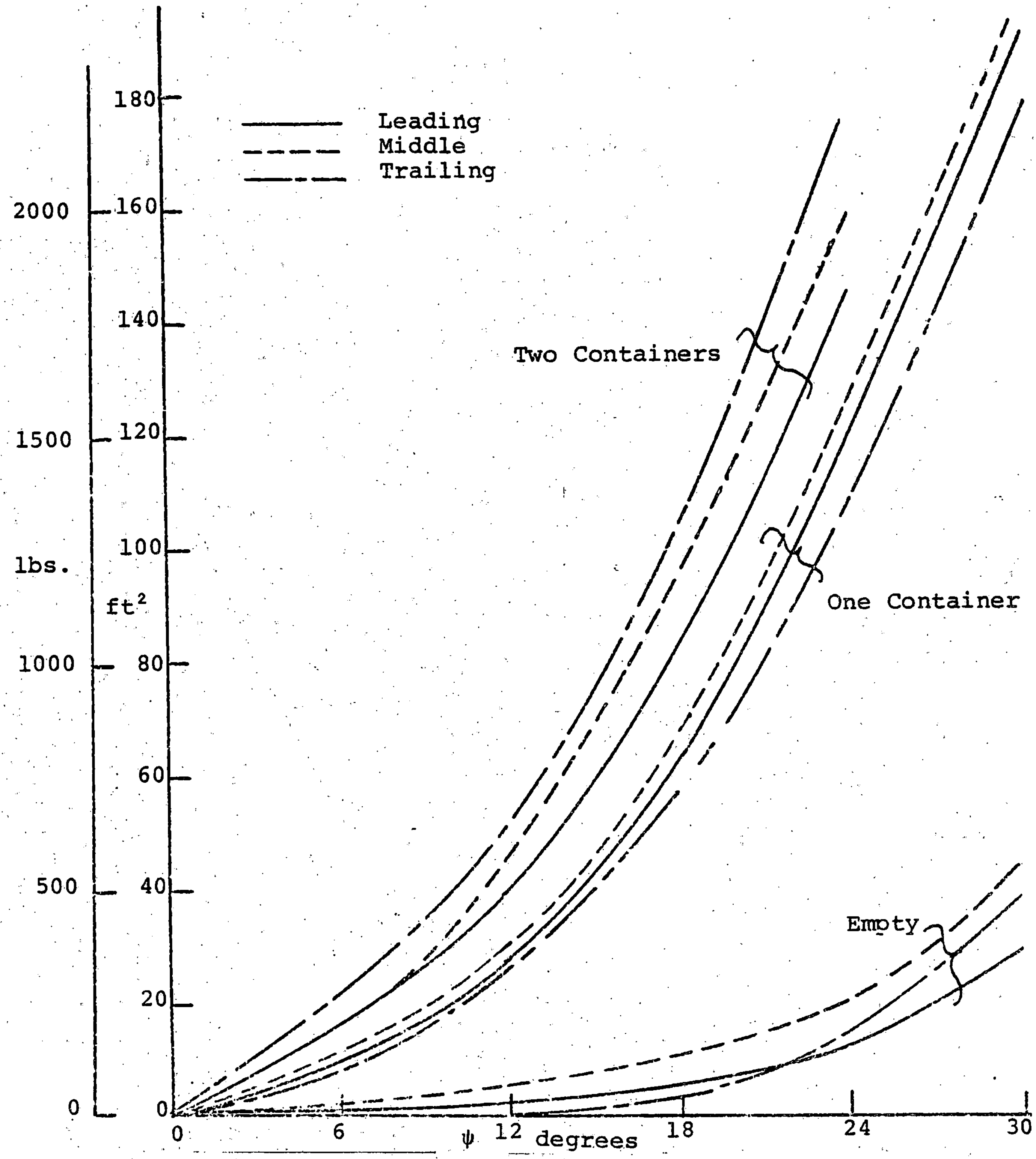


Figure 28. Lift Force Per Unit of Southern Pacific Double Stack Articulated Container Car as a Function of Yaw Angle. Force Given as a Force Area and for 70 mph Relative Wind Velocity.

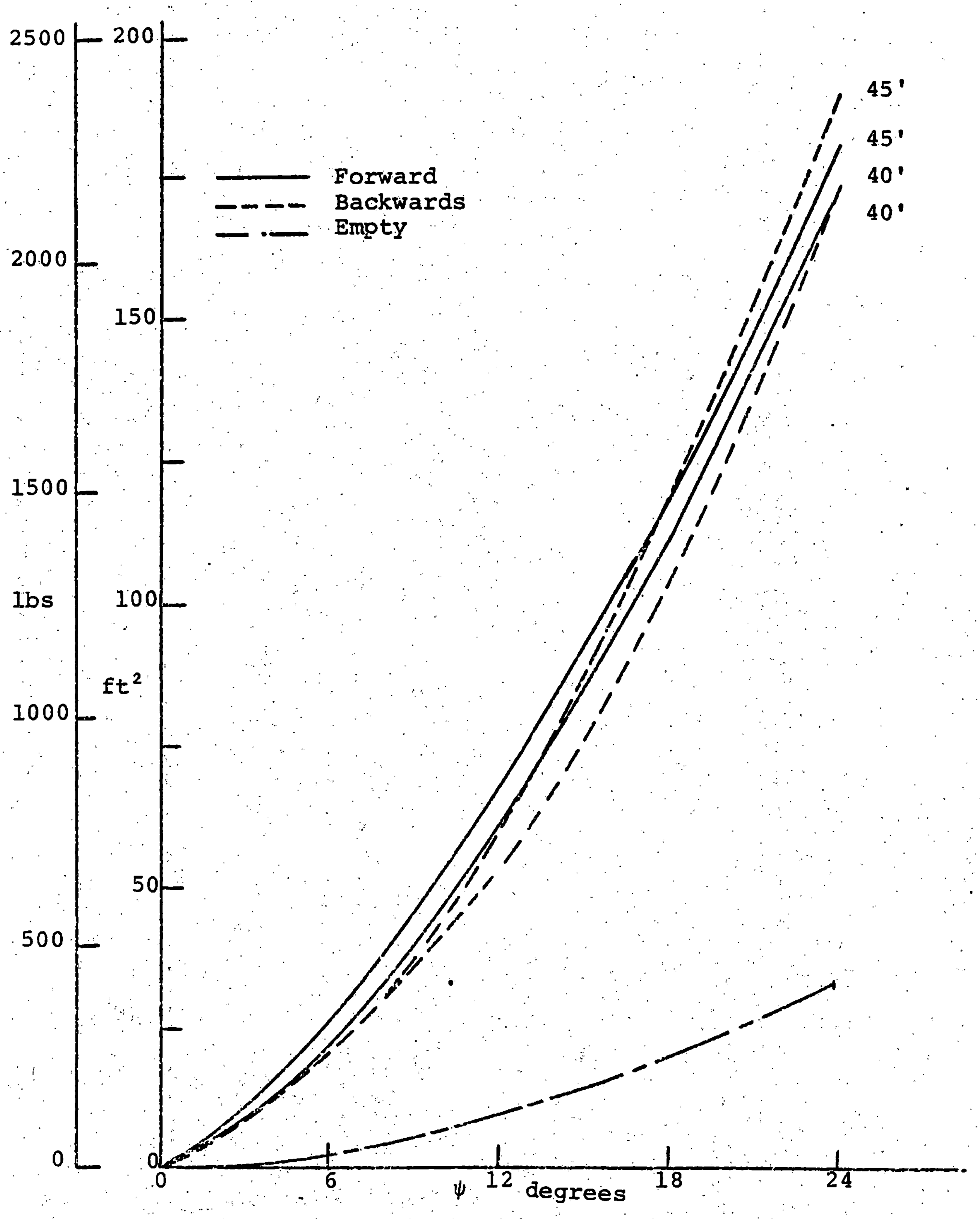


Figure 29. Side Force Per Unit of Trailer Train Prototype Car as a Function of Yaw Angle. Force Given as a Force Area and for 70 mph Relative Wind Velocity.

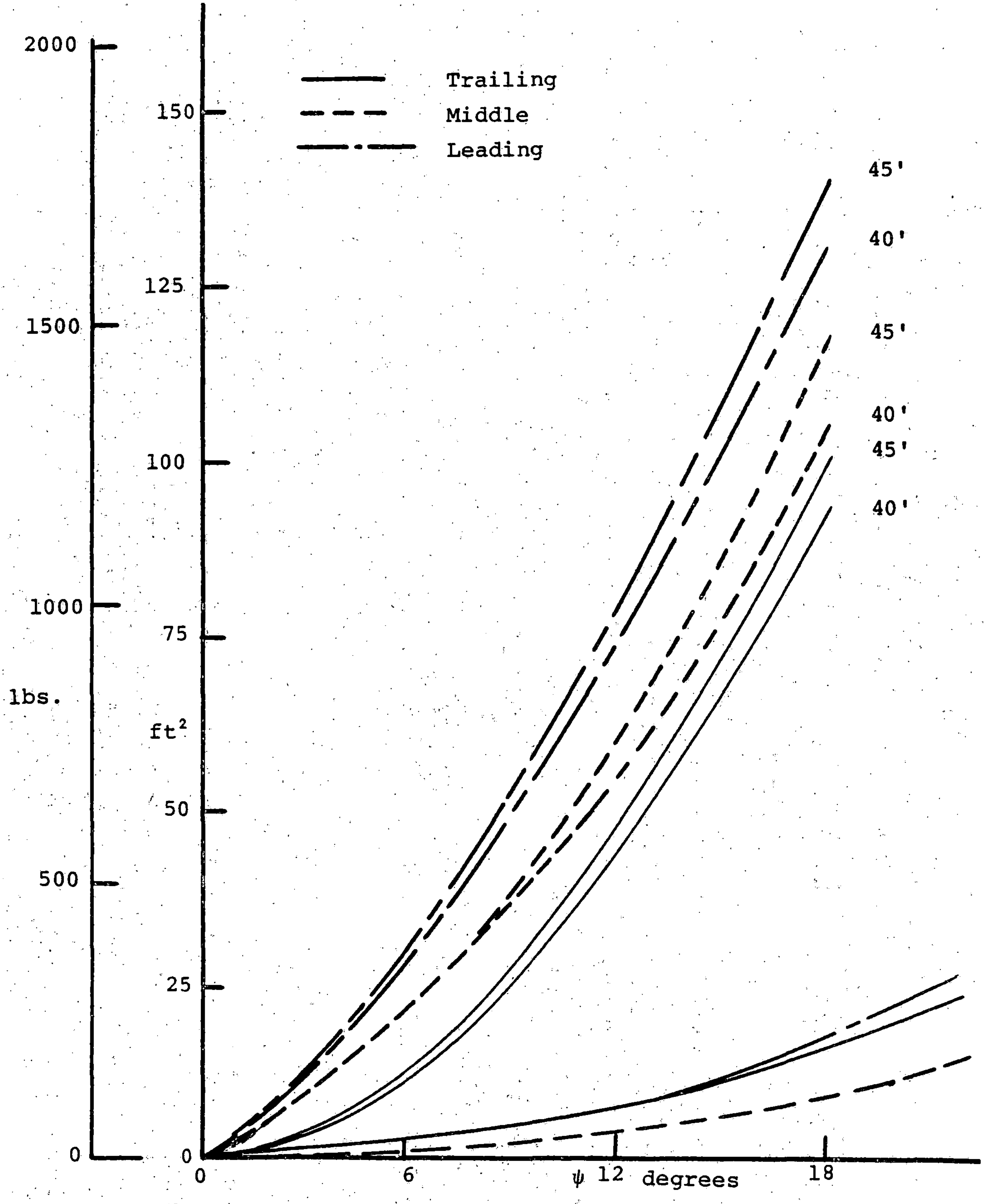


Figure 30a. Side Force on Santa Fe Units with 45 and 40 Foot Trailers Facing Forward as a Function of Yaw Angle. Lift Force is Given as a Force Area and for 70 mph Relative Wind Velocity.

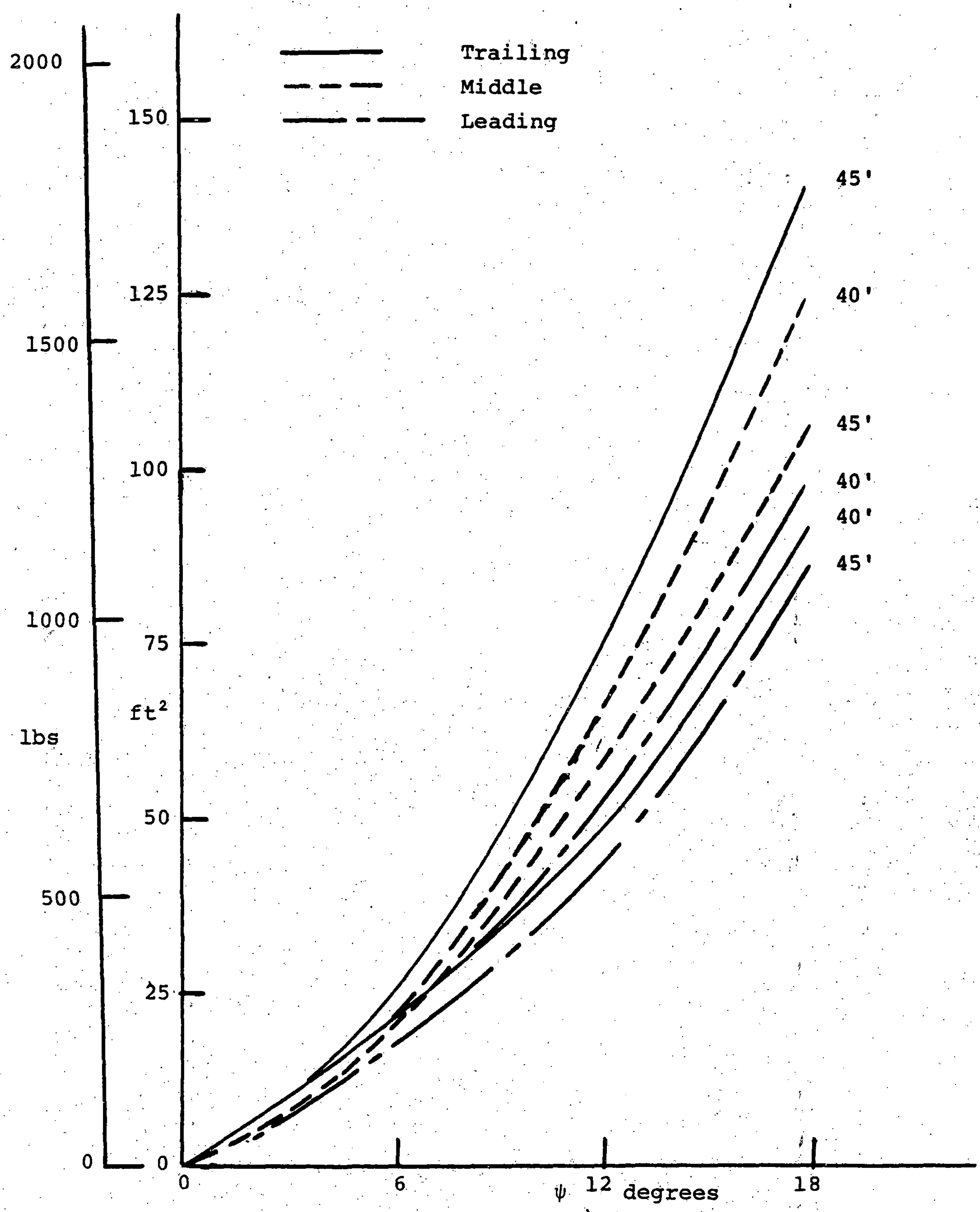


Figure 30b. Side Force on Santa Fe Units with 45 and 40 Foot Trailers Facing Backwards as a Function of Yaw Angle. Lift Force is Given as a Force Area and for 70 mph Relative Wind Velocity.

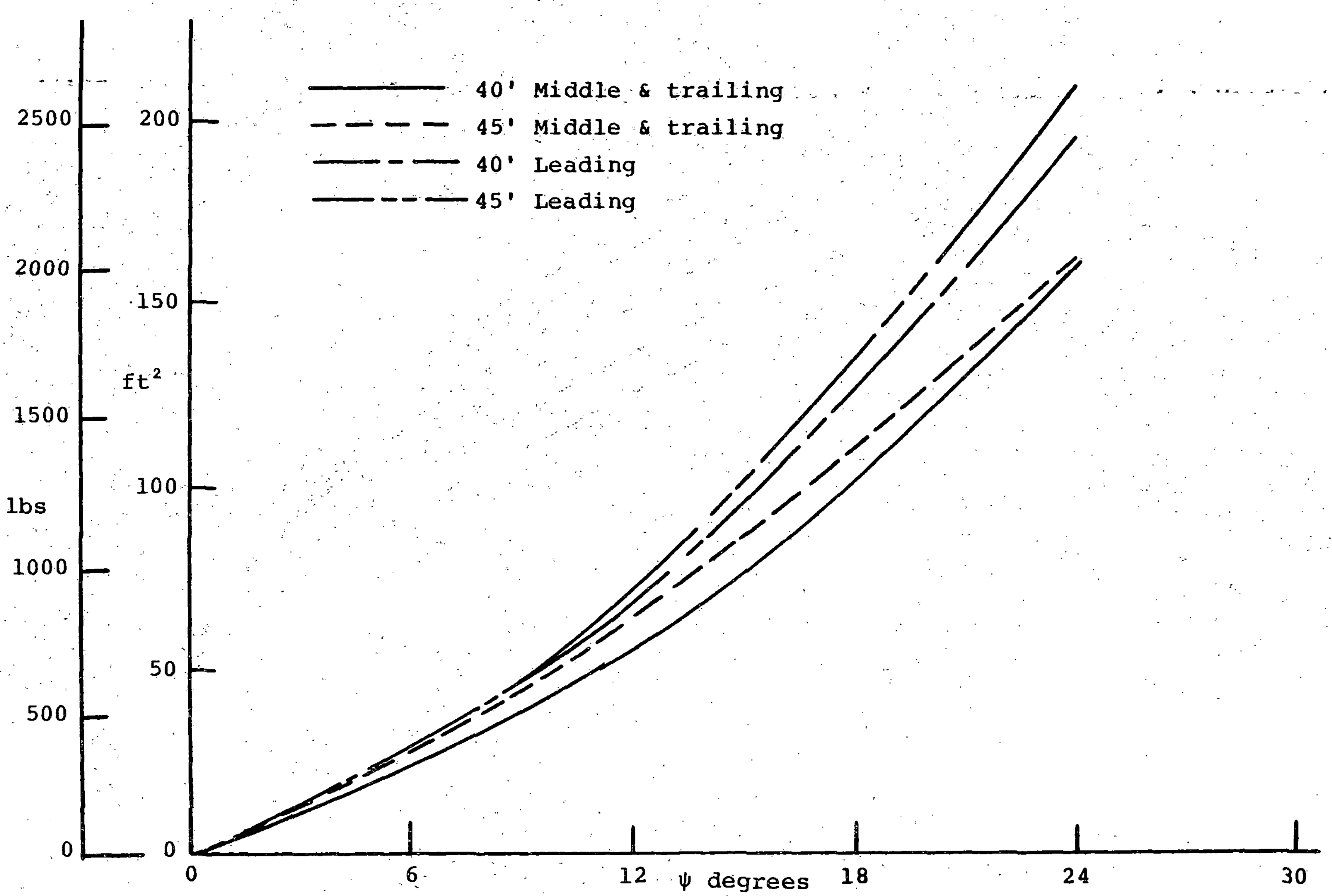


Figure 31a. Side Force on Paton Lo Pro Unit with 45 and 40 Foot Trailers Facing Forward as a Function of Yaw Angle. Side Force is Given as a Force Area and for 70 mph Relative Wind Velocity.

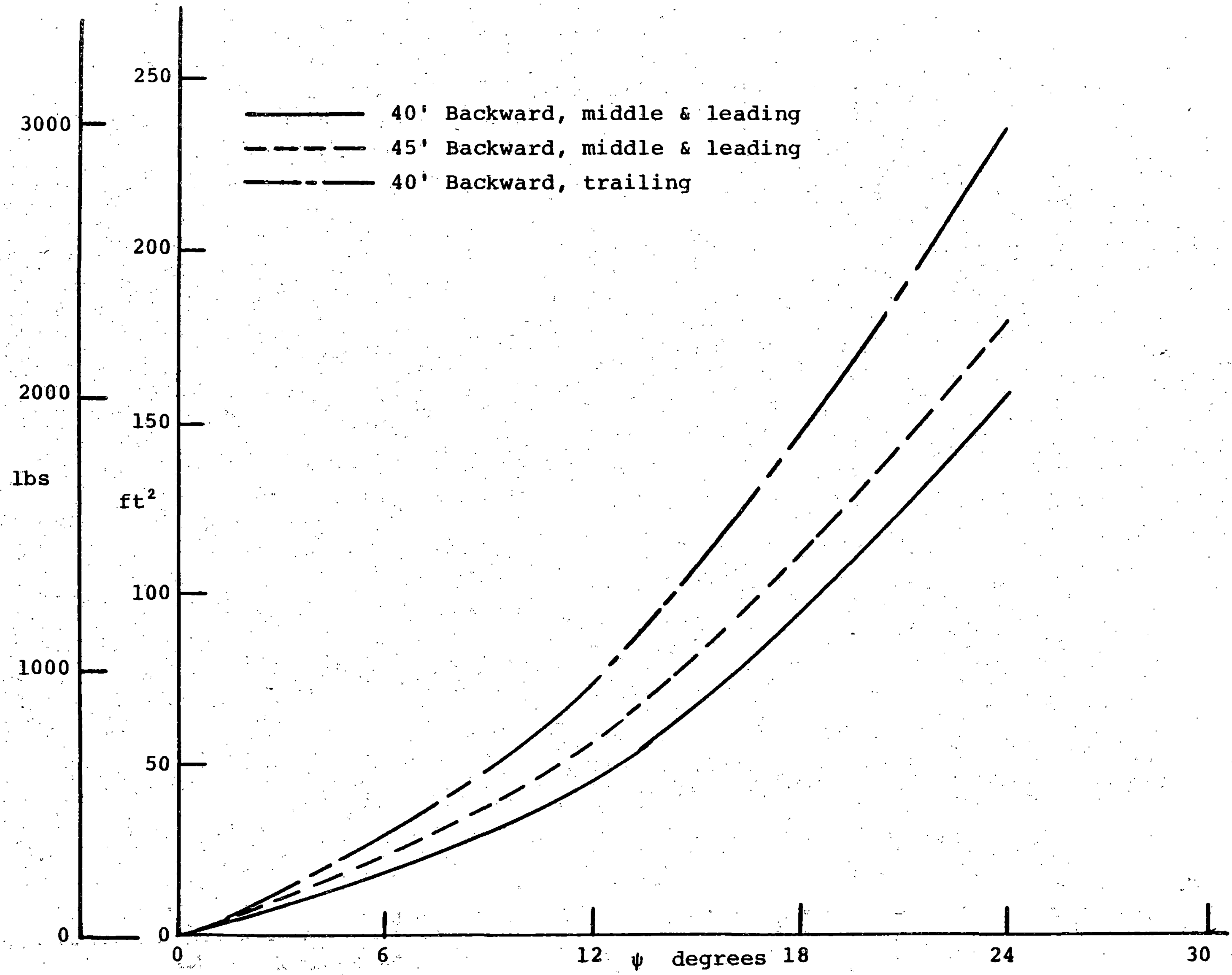


Figure 31b. Side Force on Paton Lo Pro Unit with 45 and 40 Foot Trailers Facing Backwards as a Function of Yaw Angle. Side Force is Given as a Force Area and for 70 mph Relative Wind Velocity.

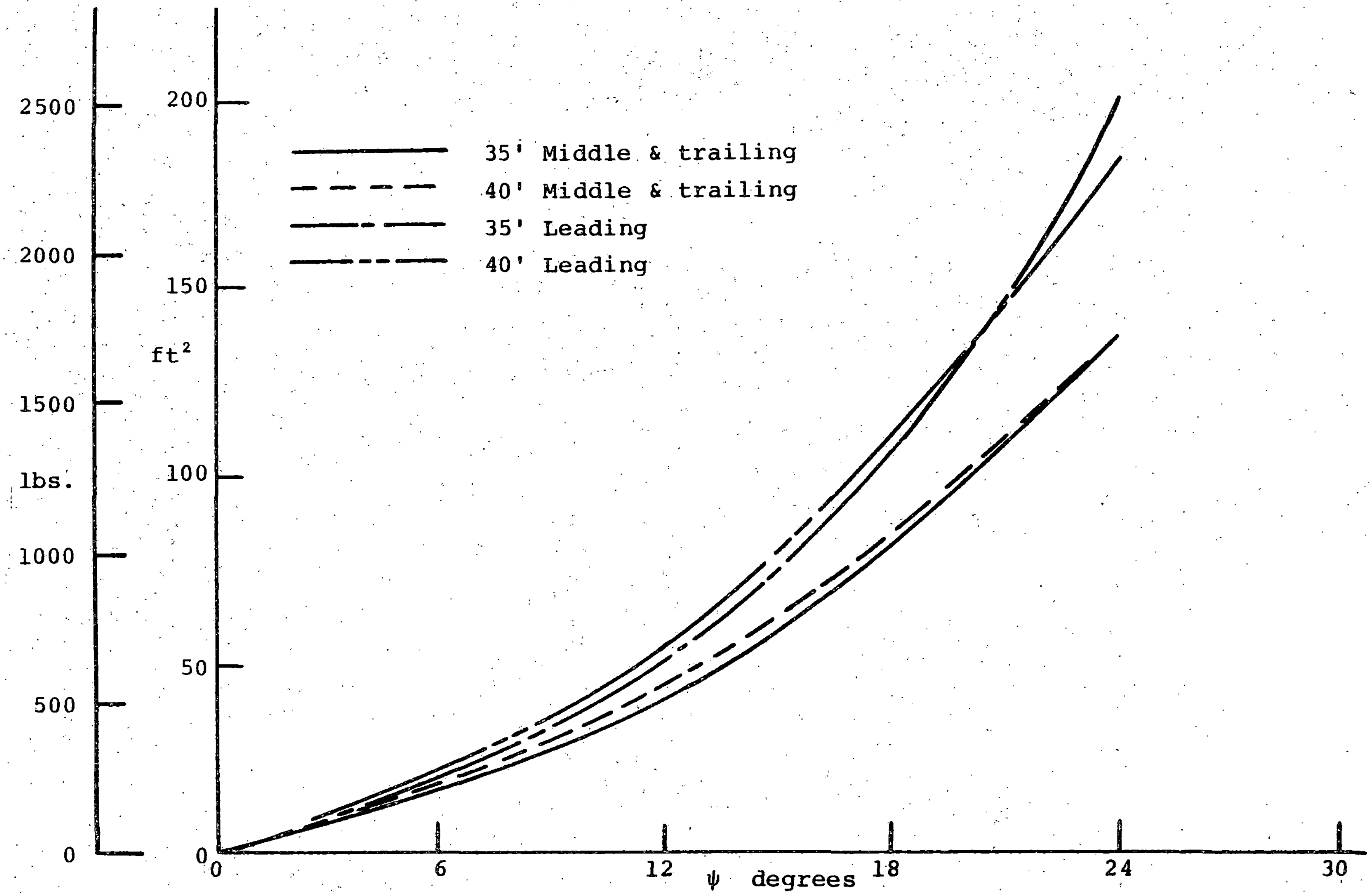


Figure 31c. Side Force on Paton Lo Pro Unit with 40 and 35 Foot Containers as a Function of Yaw Angle. Force Given as a Force Area and for 70 mph Relative Wind Velocity.

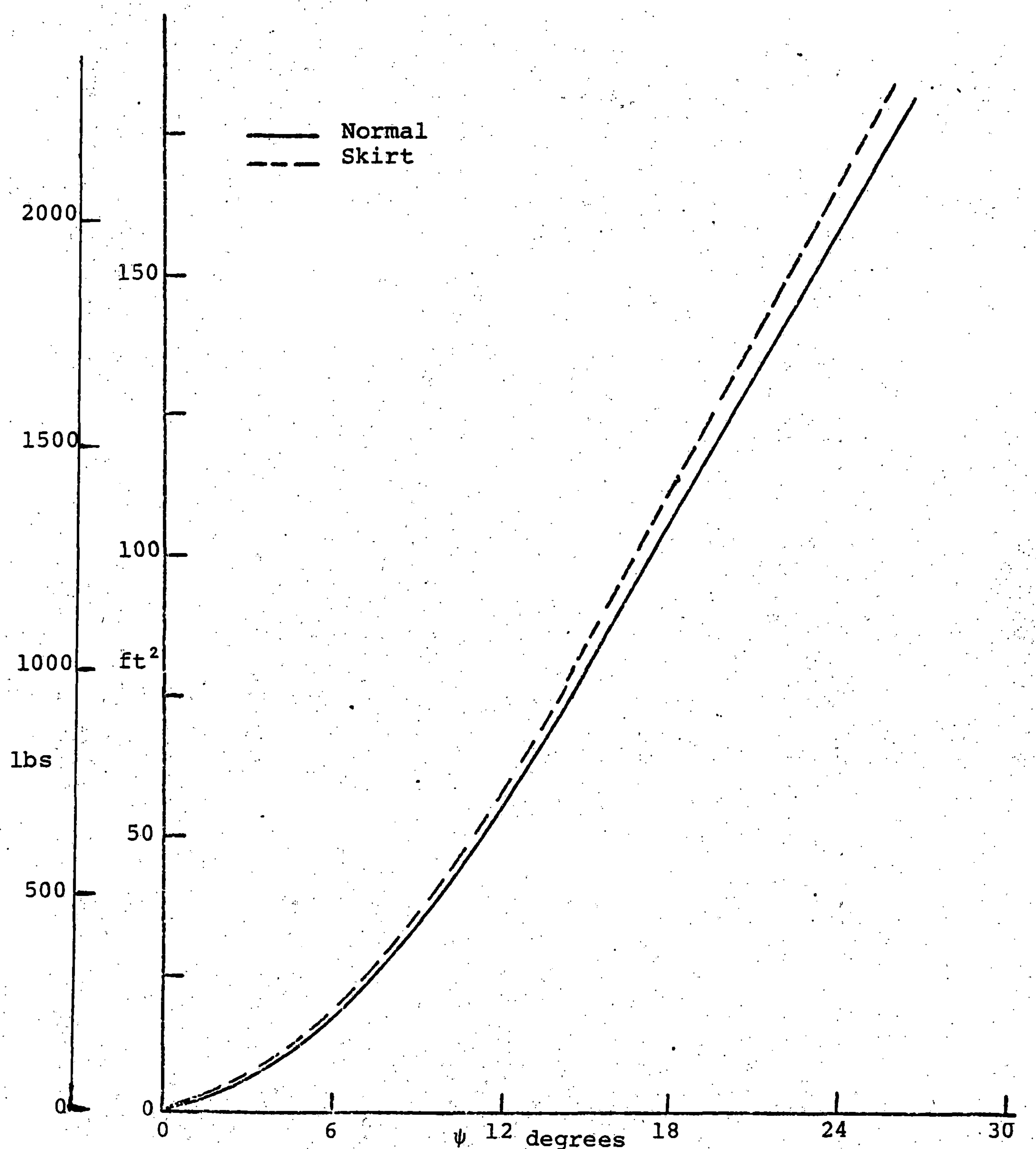


Figure 32. Side Force Per Unit of Roadrailer as a Function of Yaw Angle. Force Given as a Force Area and for 70 mph Relative Wind Velocity.

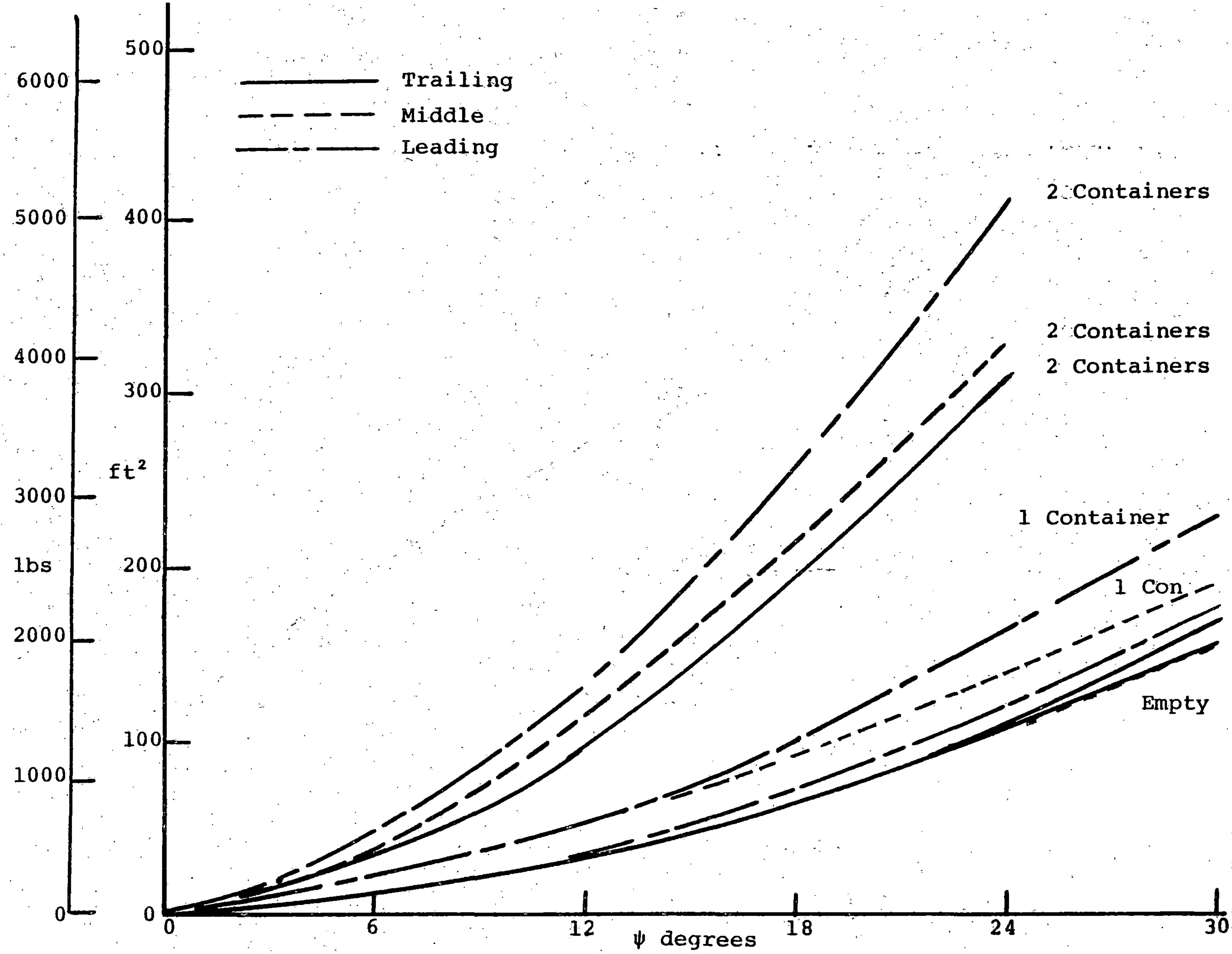


Figure 33. Side Force on Units of the Southern Pacific Double Stack Articulated Container Car as a Function of Yaw Angle for One and Two 40 Foot Containers and Empty. Force is Given as a Force Area and for 70 mph Relative Wind Velocity.

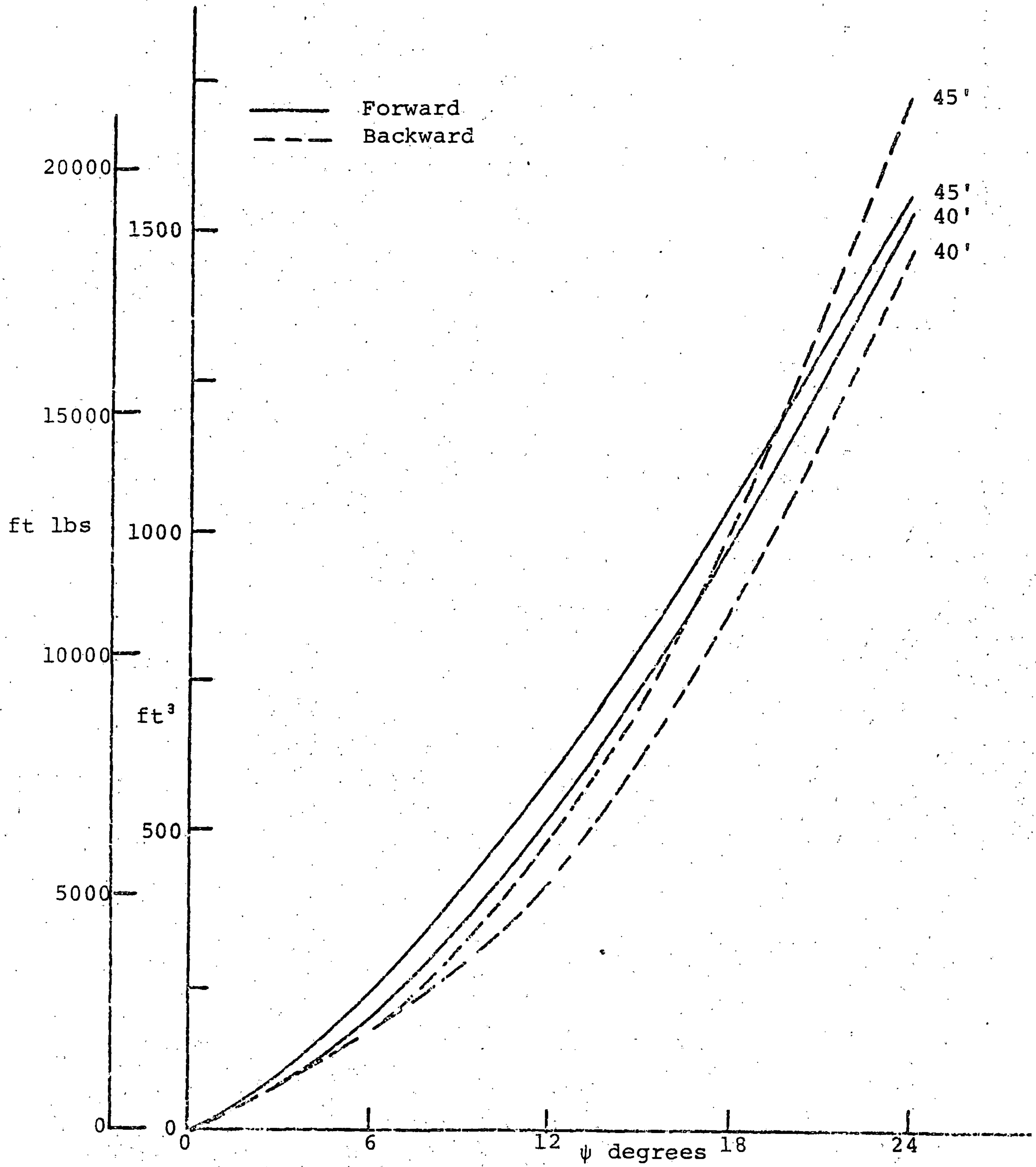


Figure 34. Rolling Moment Per Unit of Trailer Train Prototype Car as a Function of Yaw Angle. Moment is Given for Moment Volume and for 70 mph Relative Wind Velocity.

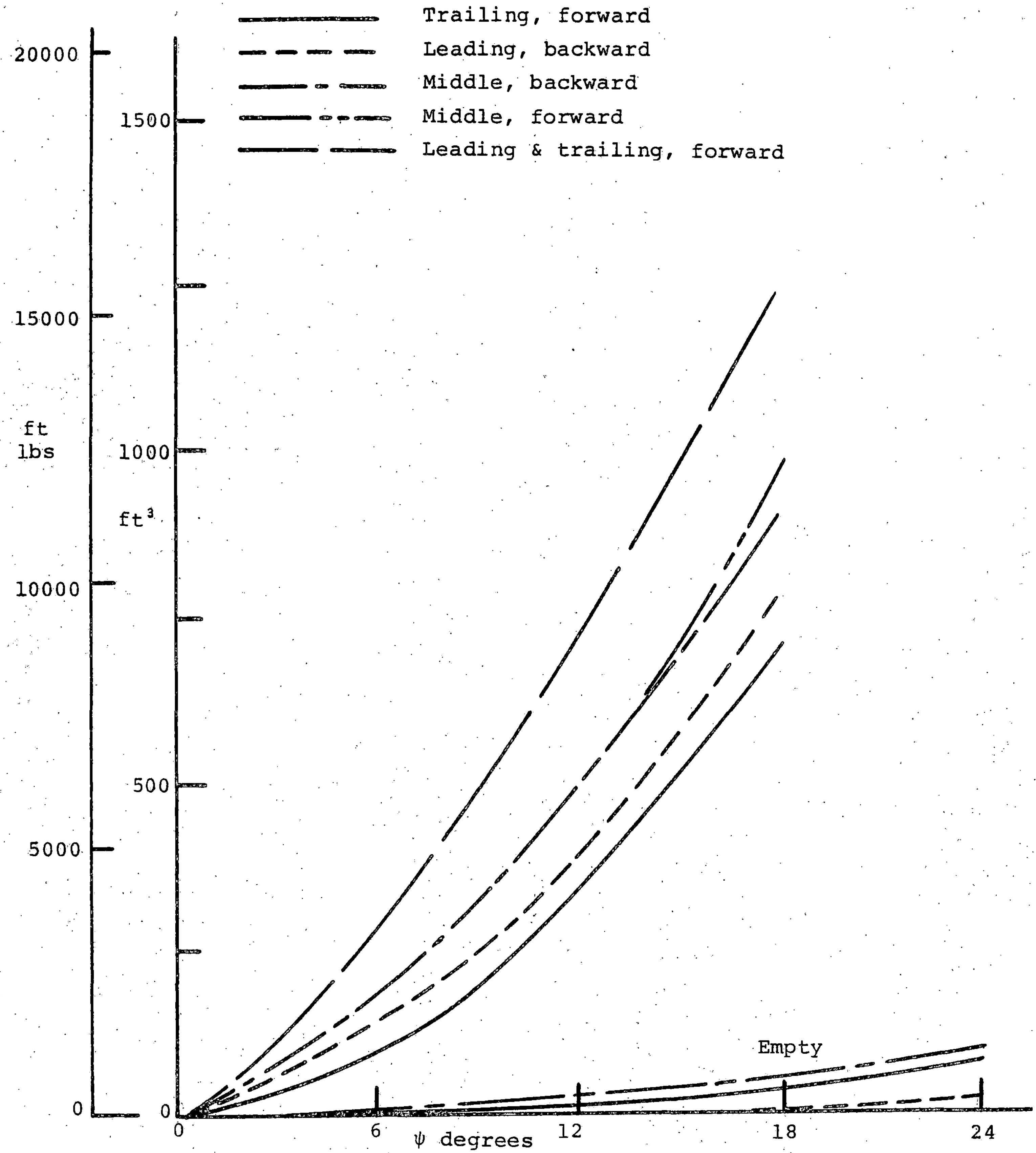


Figure 35a. Rolling Moment Per Unit of the Santa Fe 10 Pac as a Function of Yaw Angle for 45 Foot Trailers and Empty. Moment Given for Moment Volume and for 70 mph Relative Wind Velocity.

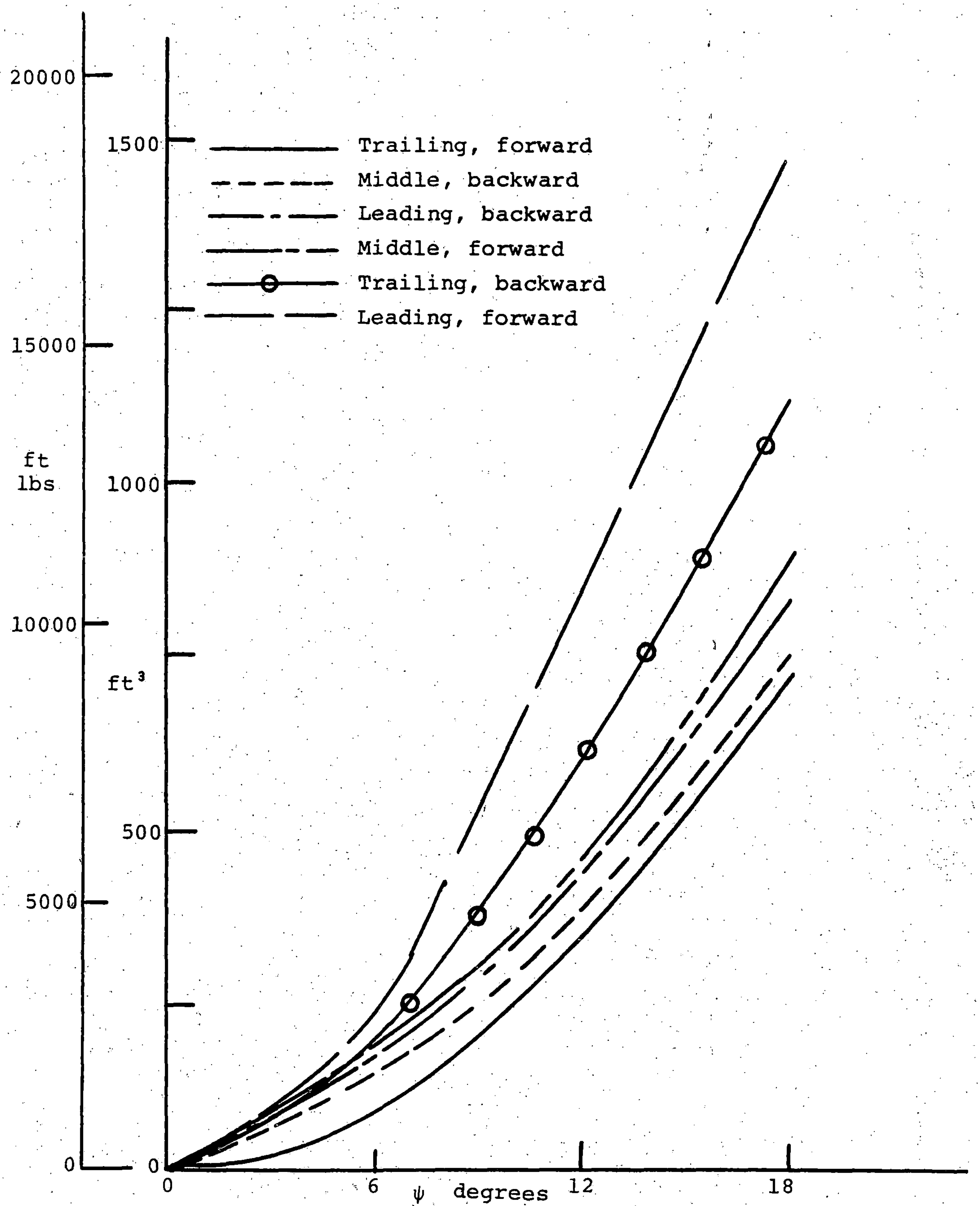


Figure 35b. Rolling Moment Per Unit of the Santa Fe 10 Pac as a Function of Yaw Angle for 40 Foot Trailers. Moment Given for Moment Volume and for 70 mph Relative Wind Velocity.

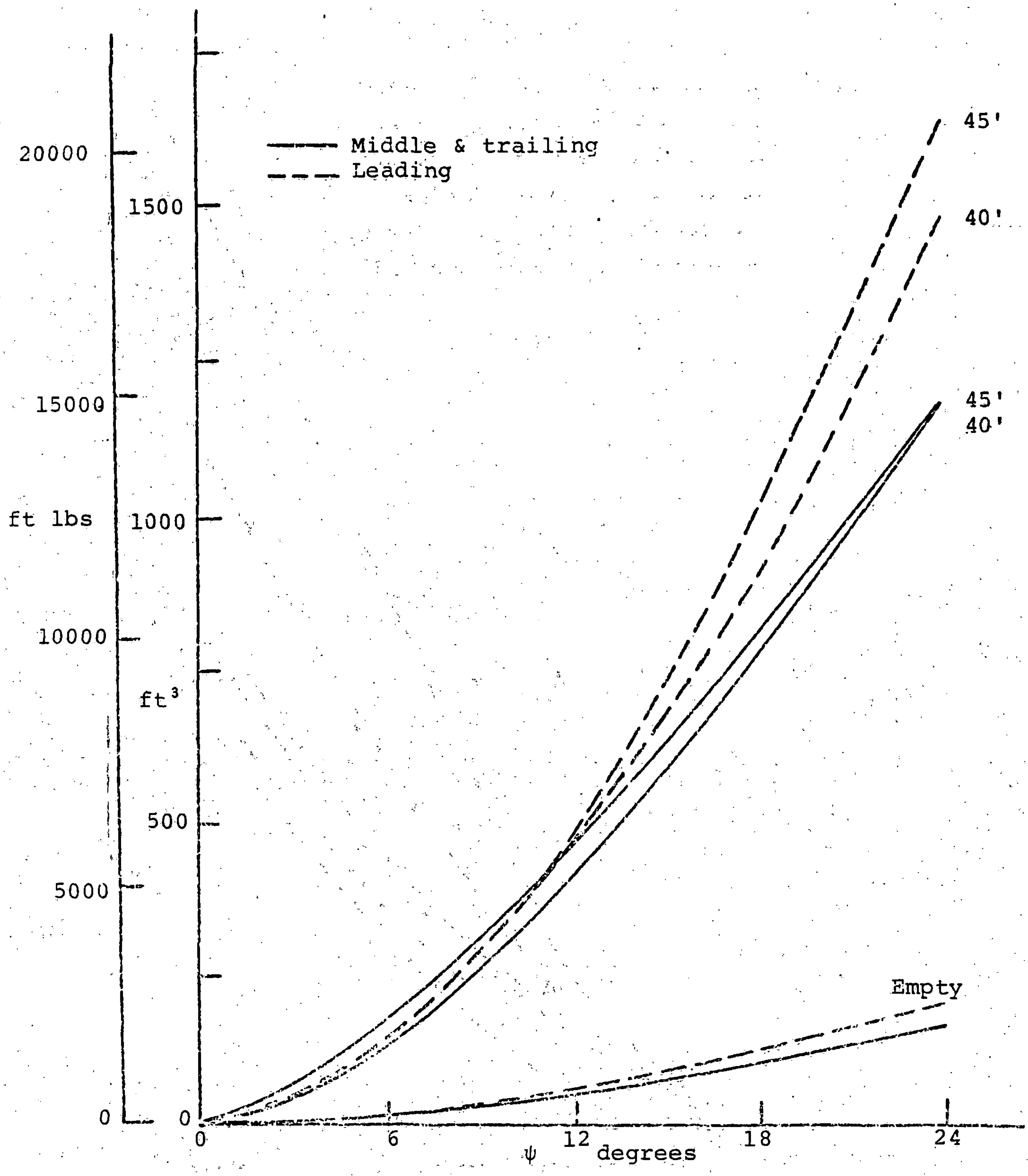


Figure 36a. Rolling Moment Per Unit of Paton Lo Pro Car as a Function of Yaw Angle for 45 and 40 Foot Trailers Facing Forward. Moment Given for Moment Volume and for 70 mph Relative Wind Velocity.

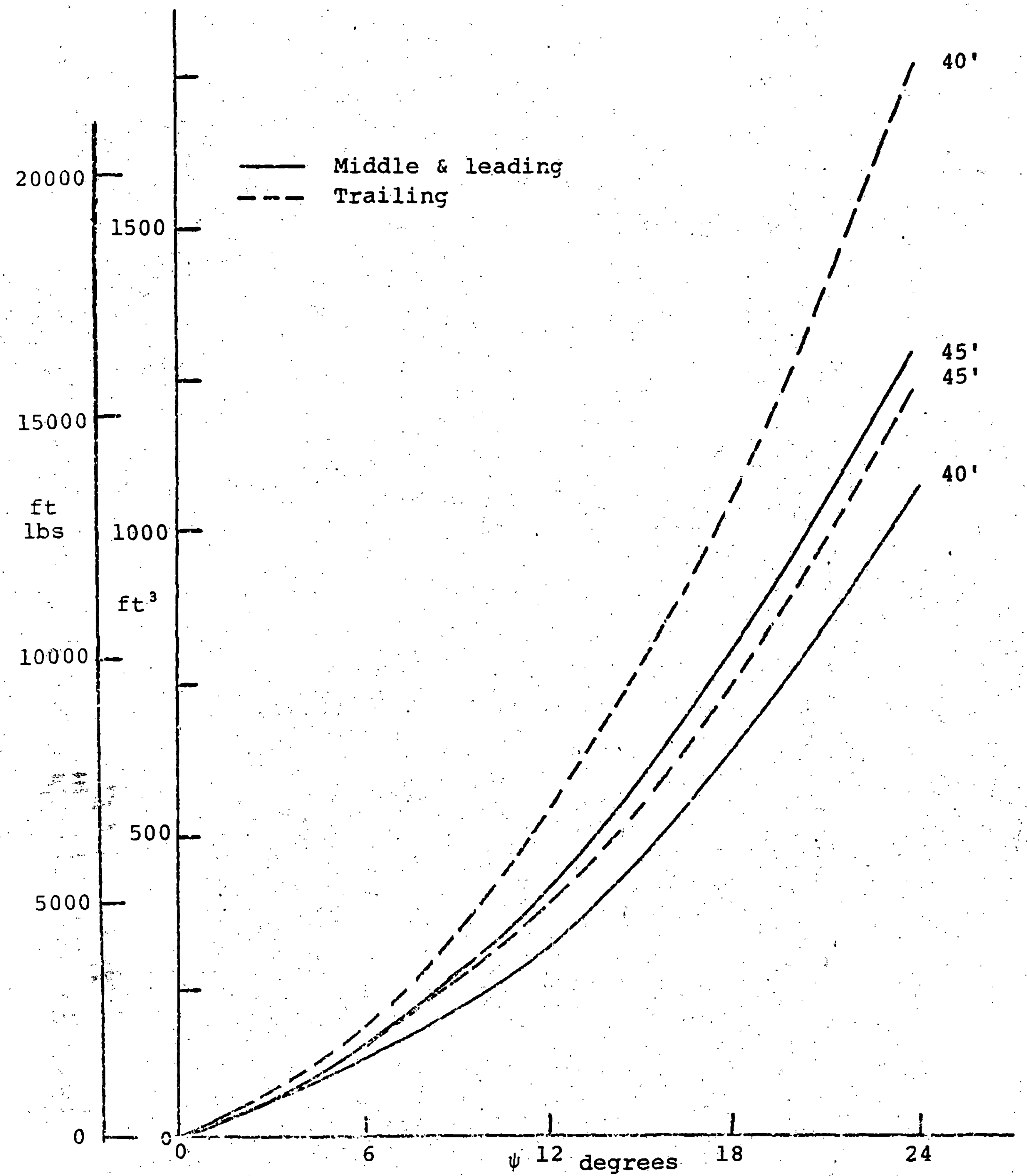


Figure 36b. Rolling Moment Per Unit of Paton Lo Pro Car as a Function of Yaw Angle for 45 and 40 Foot Trailers Facing Backward. Moment Given for Moment Volume and for 70 mph Relative Wind Velocity.

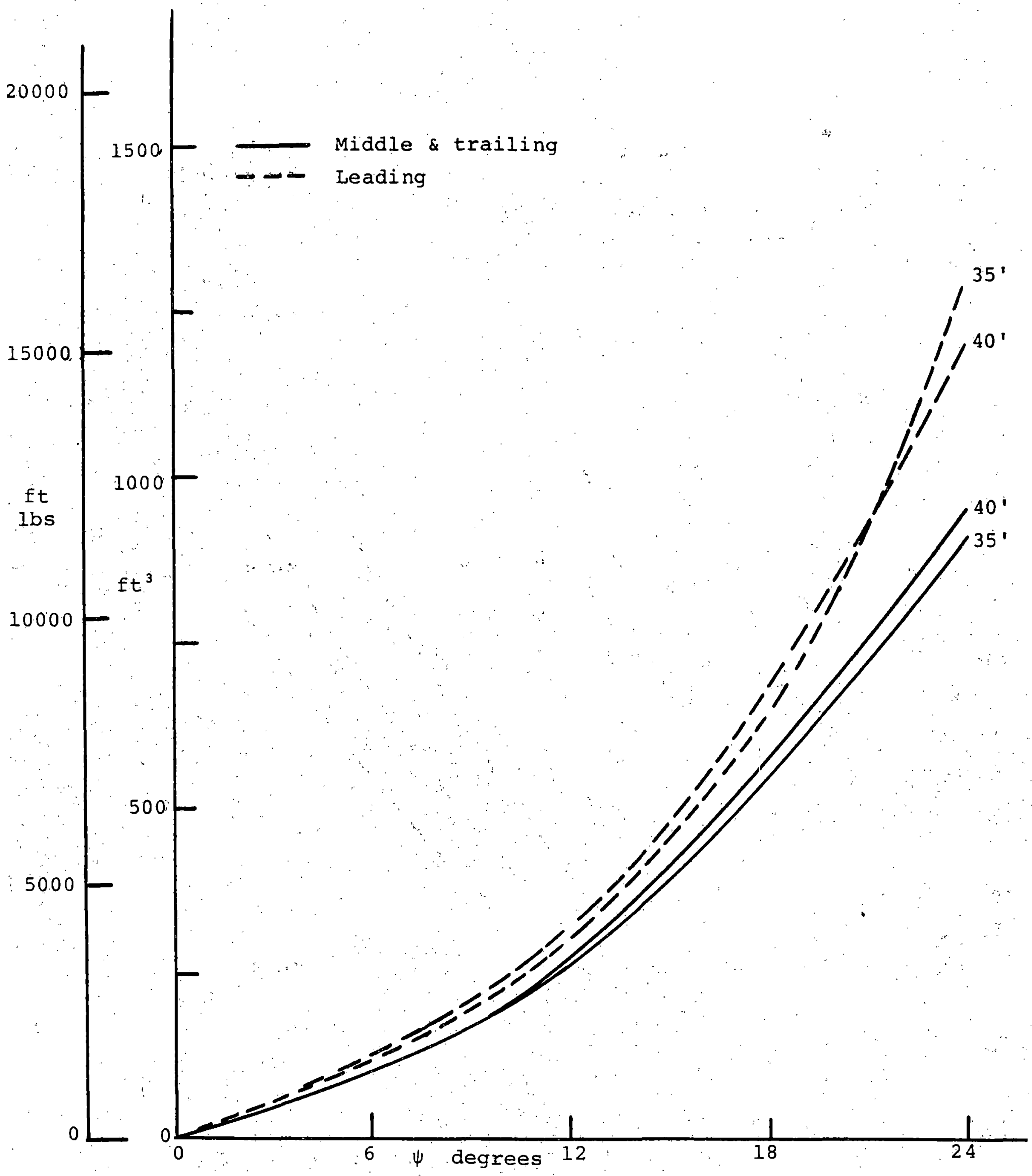


Figure 36c. Rolling Moment Per Unit of Paton Lo Pro Car as a Function of Yaw Angle for 40 and 35 Foot Containers. Moment Given for Moment Volume and for 70 mph Relative Wind Velocity.

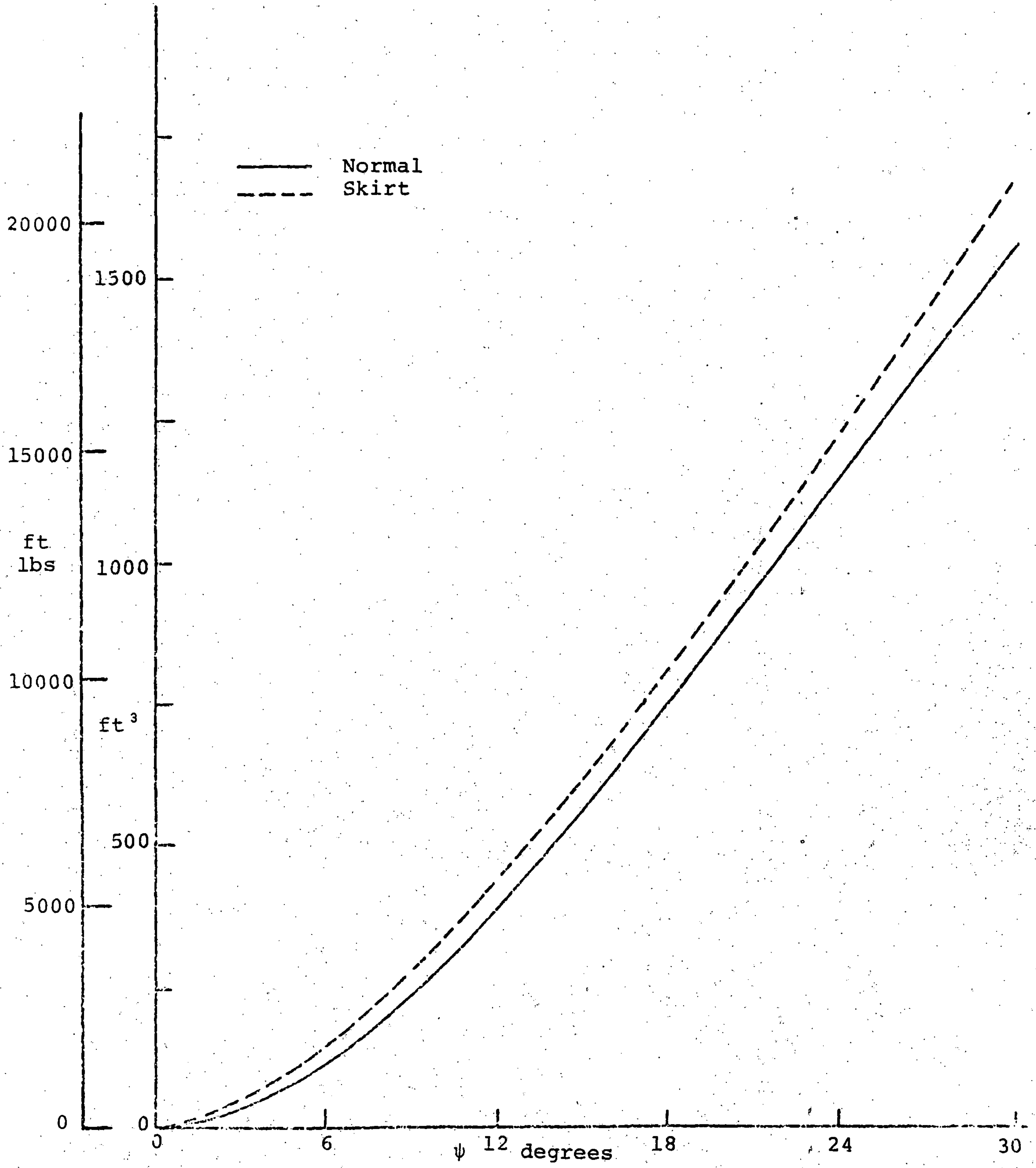


Figure 37. Rolling Moment Per Unit of Roadrailer as a Function of Yaw Angle. Moment Given for Moment Volume and for 70 mph Relative Wind Velocity.

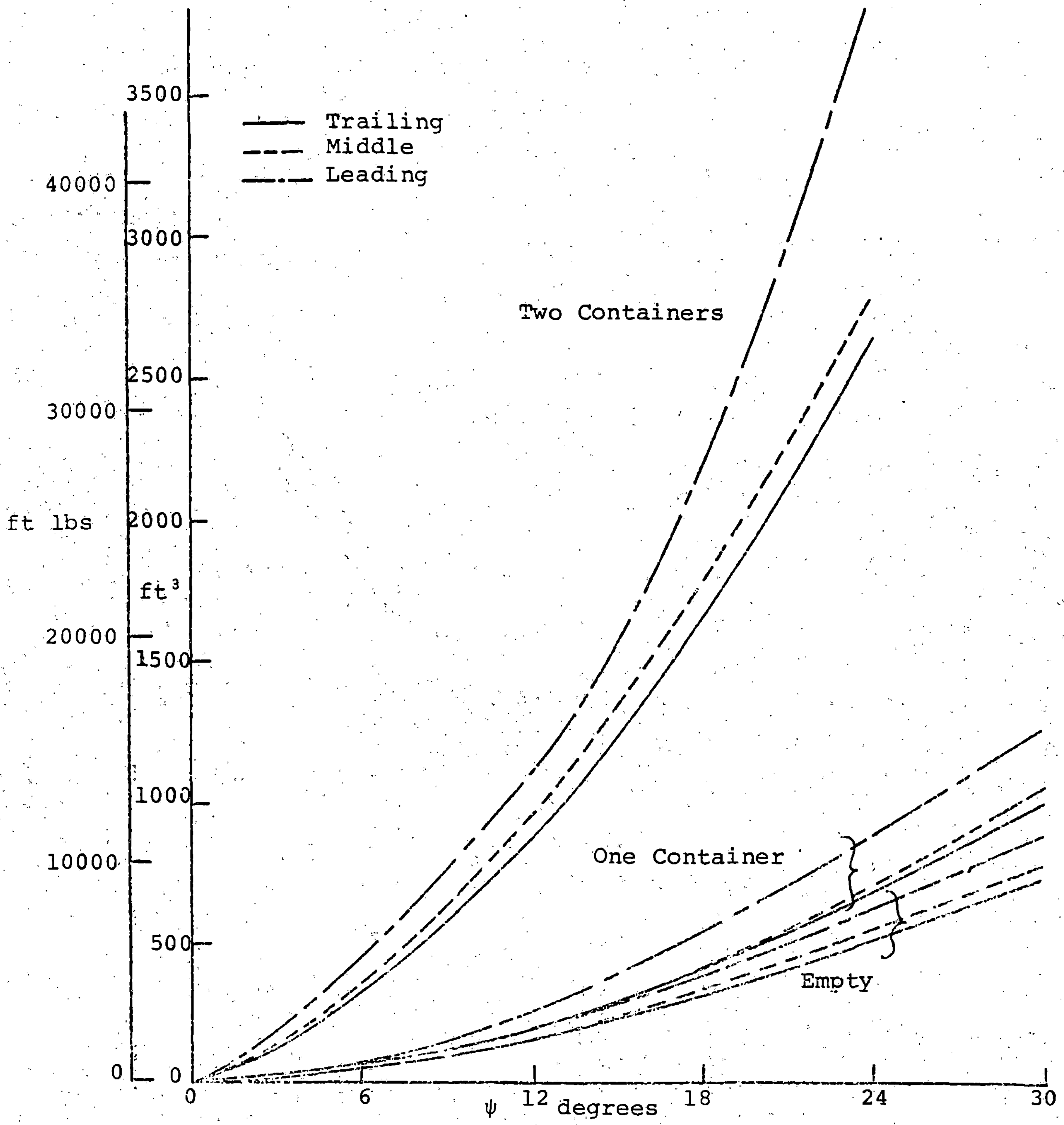


Figure 38. Rolling Moment Per Unit of Southern Pacific Double Stack Articulated Container Car as a Function of Yaw Angle. Moment Given for Moment Volume and for 70 mph Relative Wind Velocity.

TABLE 1

DYNAMIC PRESSURE q AS A FUNCTION OF RELATIVE WIND VELOCITY V_R

V_R (mph)	q (#/ft^2)
10	.2553
20	1.0214
30	2.298
40	4.085
50	6.384
60	9.193
70	12.513
80	16.343
90	20.684
100	25.536

TABLE 2

AXIAL FORCE AREA $\cdot C_A A$

($ft.^2$)

For 1 or 2 Units as Specified

	YAW ANGLE 0	6	12	18	24	30
UNITS ON BALANCE						
SANTA FE						
45 ft. trailers, facing forward						
Leading, middle	46.63	59.55	99.79	117.43		
Middle, middle	37.93	48.66	79.49	97.24	103.79	
Middle, trailing	41.87	54.49	94.85	117.76		
40 ft. trailers, facing forward						
Leading, middle	47.19	57.08	97.09	113.23		
Middle, middle	52.42	56.00	90.71	108.43	119.42	
Middle, trailing	55.74	65.41	107.85	147.92		
45 ft. trailers, facing backward						
Trailing, middle	44.70	60.31	106.87	127.31	143.54	
Middle, middle	44.03	56.98	94.20	111.23		
Middle, leading	50.89	66.54	110.40	130.59		
40 ft. trailers, facing backward						
Trailing, middle	53.09	71.37	117.51	153.61	181.09	
Middle, middle	51.48	70.67	129.03	159.23	168.43	
Middle, leading	53.17	78.26	146.33	179.51		
Empty, facing forward						
Leading, middle	14.27	19.50	27.43	37.85	44.29	
Middle, middle	16.56	20.84	28.65	34.68	38.97	43.13
Middle, trailing	16.35	24.46	32.76	37.32	42.66	45.89

TABLE 2 (continued)

	YAW ANGLE					
	0	6	12	18	24	30
UNITS ON BALANCE						
PATON LO PRO						
40 ft. trailer, facing forward						
Middle, middle	42.47	46.96	85.20	106.38	124.73	
Trailing, leading	47.89	55.84	93.88	125.75	153.70	
45 ft. trailer, facing forward						
Middle, middle	37.55	42.07	81.96	94.93	108.05	
Trailing, leading	47.53	54.33	87.92	117.32	140.55	
40 ft. trailer, facing backward						
Middle, middle	37.68	50.03	100.11	137.29	159.86	
Leading, trailing	51.38	63.89	117.18	156.24	182.80	
45 ft. trailer, facing backward						
Middle, middle	32.41	50.31	106.42	138.78	164.70	
Leading, trailing	57.24	68.74	122.26	163.81	188.38	204.53
Empty, facing forward						
Middle, middle	19.00	19.79	26.14	33.07	41.32	47.76
Trailing, leading	21.40	22.91	27.55	35.77	47.32	55.92
40 ft. container						
Middle, middle	34.14	37.99	66.57	84.05	94.53	
Trailing, leading	46.02	47.88	83.55	108.89	125.80	
35 ft. container						
Middle, middle	29.36	37.77	76.06	102.59	126.65	
Trailing, leading	40.92	52.59	86.67	117.37	157.31	

TABLE 2 (continued)

	YAW ANGLE					
	0	6	12	18	24	30
UNITS ON BALANCE						
SOUTHERN PACIFIC DOUBLE STACK						
Two 40 ft. containers						
Middle	20.29	23.77	38.64	46.56	54.98	
Trailing	26.95	27.66	30.58	40.30	53.81	60.59
Leading	41.02	48.85	75.47	99.13	113.96	
One 40 ft. container						
Middle	16.63	19.92	30.59	36.46	41.00	40.96
Trailing	17.78	20.33	23.08	32.11	35.82	37.56
Leading	30.87	35.14	49.23	60.96	67.94	71.83
Empty						
Middle	38.97	50.37	73.69	87.86	95.81	101.99
Trailing	38.03	48.45	69.91	84.02	88.95	91.87
Leading	61.22	74.74	111.29	137.66	147.32	149.45
TRAILER TRAIN PROTOTYPE						
Two 45 ft. trailers						
Facing forward	62.32	63.71	106.01	127.32	147.72	
Facing backward	63.56	80.78	149.49	175.39	188.38	
Two 40 ft. trailers						
Facing forward	68.54	66.93	111.04	140.63	170.03	
Facing backward	67.77	83.34	148.48	188.48	219.02	
Empty	22.93	29.58	45.53	58.06	63.58	69.40
ROADRAILER						
Two	29.85	37.56	60.64	70.37	76.63	76.91
Two with skirt	25.34	29.95	44.73	55.66	62.64	65.45

TABLE 3

LIFT FORCE AREA

(ft.^{2})

For 1 or 2 units as specified

	YAW ANGLE 0	6	12	18	24	30
UNITS ON BALANCE						
SANTA FE						
45 ft. trailers, facing forward						
Leading, middle	- 1.62	22.86	68.97	139.85		
Middle, middle	- 4.10	15.12	53.87	121.01	251.68	
Middle, trailing	- 1.79	23.02	46.22	90.73		
40 ft. trailers, facing forward						
Leading, middle	0.74	21.31	58.01	129.86		
Middle, middle	- 1.34	14.92	50.78	125.36	249.10	
Middle, trailing	- 1.29	17.25	42.28	119.70		
45 ft. trailers, facing backward						
Trailing, middle	0.06	21.70	54.44	119.18	229.95	
Middle, middle	- 0.89	17.24	53.23	126.21		
Middle, leading	- 2.47	15.50	52.58	119.80		
40 ft. trailers, facing backward						
Trailing, middle	- 1.90	16.76	47.84	114.43	196.70	
Middle, middle	- 0.70	11.84	27.97	79.14	168.11	
Middle, leading	- 3.03	10.73	28.85	83.58		
Empty, facing forward						
Leading, Middle	2.07	5.88	9.70	19.13	27.33	
Middle, middle	3.75	5.75	9.37	14.27	20.29	29.78
Middle, trailing	4.05	7.91	11.83	20.65	31.71	40.72

TABLE 3 (continued)

	YAW ANGLE					
	0	6	12	18	24	30
UNITS ON BALANCE						
<u>PATON LO PRO</u>						
40 ft. trailers, facing forward						
Middle, middle	5.53	25.04	68.66	144.34	248.82	
Trailing, leading	8.95	32.31	80.06	159.26	270.03	
45 ft. trailers, facing forward						
Middle, middle	7.47	27.77	62.60	151.39	292.39	
Trailing, leading	10.44	34.78	80.88	173.44	316.15	
40 ft. trailers, facing backward						
Middle, middle	3.91	25.31	65.00	141.27	237.62	
Leading, trailing	4.56	26.21	65.27	154.78	286.75	
45 ft. trailers, facing backward						
Middle, middle	- 0.59	22.22	59.63	140.88	256.77	
Leading, trailing	11.01	30.79	73.43	150.24	251.44	363.47
Empty						
Middle, middle	9.08	18.22	31.86	57.18	75.66	91.18
Leading, trailing	12.43	22.53	36.94	60.82	83.22	106.19
40 ft. containers						
Middle, middle	6.52	25.68	69.46	148.79	266.10	
Trailing, leading	9.49	31.36	71.67	139.97	253.47	
35 ft. containers						
Middle, middle	7.77	26.88	69.31	148.79	243.03	
Trailing, leading	12.46	34.06	72.29	142.19	253.64	

TABLE 3 (continued)

	YAW ANGLE 0	6	12	18	24	30
UNITS ON BALANCE						
SOUTHERN PACIFIC DOUBLE STACK						
Two 40 ft. containers						
Middle	- 0.22	16.25	48.65	94.35	159.67	
Trailing	10.82	19.58	39.09	78.61	144.93	219.60
Leading	- 1.14	20.84	49.44	103.86	174.51	
One 40 ft. container						
Middle	- 0.37	9.53	30.38	66.84	124.65	211.84
Trailing	3.81	12.28	25.13	62.45	122.72	190.91
Leading	- 5.30	7.58	27.24	57.03	105.49	181.10
Empty						
Middle	0.30	4.65	8.52	9.86	16.86	43.58
Trailing	3.02	7.10	5.80	4.77	9.84	28.79
Leading	- 6.41	- 0.09	1.49	2.11	13.62	39.32
TRAILER TRAIN PROTOTYPE						
Two 45 ft. trailers						
Facing forward	- 4.78	18.63	47.72	148.12	283.83	
Facing backward	1.23	17.78	52.53	129.03	254.66	
Two 40 ft. trailers						
Facing forward	0.08	21.56	62.54	141.28	249.28	
Facing backward	0.41	18.43	57.89	118.74	215.37	
Empty	0.02	5.21	9.32	18.49	30.29	41.33
ROADRAILER						
Two	- 2.15	21.26	40.02	76.56	184.63	322.91
Two with skirt	- 4.56	18.38	43.49	74.13	182.91	317.52

TABLE 4

SIDE FORCE AREA

($ft.^2$)

For 1 or 2 units as specified

	YAW ANGLE					
	0	6	12	18	24	30
UNITS ON BALANCE						
SANTA FE						
45 ft. trailers, facing forward						
Leading, middle	- 4.25	51.54	139.84	260.14		
Middle, middle	- 7.99	45.37	119.88	236.97	352.33	
Middle, trailing	-13.25	35.46	108.95	220.15		
40 ft. trailers, facing forward						
Leading, middle	- 9.31	46.54	130.46	237.06		
Middle, middle	-10.36	45.69	107.15	210.58	328.29	
Middle, trailing	-11.94	34.58	98.10	193.66		
45 ft. trailers, facing backward						
Trailing, middle	- 2.40	43.43	132.08	244.27	376.96	
Middle, middle	-12.68	45.40	111.06	211.07		
Middle, leading	-12.69	40.59	96.72	190.84		
40 ft. trailers, facing backward						
Trailing, middle	-12.94	40.42	112.39	214.67	344.05	
Middle, middle	-11.75	40.21	93.58	180.90	287.46	
Middle, leading	-12.60	44.53	98.03	187.53		
Empty						
Leading, middle	- 0.77	2.82	10.91	26.60	53.11	
Middle, middle	- 0.80	1.14	7.60	18.18	36.60	61.35
Middle, trailing	- 0.78	3.32	11.35	24.16	46.76	74.47

TABLE 4 (continued)

	YAW ANGLE					
	0	6	12	18	24	30
UNITS ON BALANCE						
PATON LO PRO						
40 ft. trailers, facing forward						
Middle, middle	-10.14	43.12	111.86	203.30	320.04	
Trailing, leading	- 6.24	42.05	122.25	228.98	354.62	
45 ft. trailers, facing forward						
Middle, middle	-12.46	45.67	127.05	218.78	323.18	
Trailing, leading	-15.95	46.12	129.00	246.54	372.02	
40 ft. trailers, facing backward						
Middle, middle	- 9.80	35.60	92.21	183.30	307.98	
Leading, trailing	-10.24	45.04	120.42	234.34	390.68	
45 ft. trailers, facing backward						
Middle, middle	-12.02	42.15	110.77	222.12	357.97	
Leading, trailing	- 5.80	41.20	111.75	216.57	360.71	538.06
Empty						
Middle, middle	- 1.54	4.68	16.39	39.44	74.70	115.22
Leading, trailing	- 1.88	5.09	18.30	41.75	81.66	131.46
40 ft. containers						
Middle, middle	- 7.27	33.42	89.13	169.27	279.09	
Trailing, leading	- 7.77	35.35	99.22	194.97	327.09	
35 ft. containers						
Middle, middle	- 7.00	30.95	81.68	164.23	279.47	
Trailing, leading	- 7.35	31.72	91.57	189.93	341.83	

TABLE 4 (continued)

	YAW ANGLE 0	6	12	18	24	30
UNITS ON BALANCE						
SOUTHERN PACIFIC DOUBLE STACK						
Two 40 ft. containers						
Middle	- 4.85	38.24	109.72	211.99	329.23	
Trailing	-12.69	34.62	96.29	197.72	306.68	435.99
Leading	-12.90	49.23	129.82	259.27	407.28	
One 40 ft. container						
Middle	- 2.97	12.52	37.44	77.01	122.65	170.60
Trailing	- 4.97	10.24	35.20	72.07	113.40	167.88
Leading	- 4.27	15.70	50.96	102.90	163.26	227.68
Empty						
Middle	- 2.69	13.09	38.02	76.55	117.96	156.61
Trailing	- 2.84	12.34	37.26	74.66	115.87	156.70
Leading	- 2.73	16.95	50.69	95.55	138.76	181.69
TRAILER TRAIN PROTOTYPE						
Two 45 ft. trailers						
Facing forward	-13.82	53.37	137.81	235.41	361.42	
Facing backward	- 9.74	45.38	98.91	201.08	342.91	
Two 40 ft. trailers						
Facing forward	- 8.32	47.73	120.64	223.84	350.03	
Facing backward	- 8.54	45.79	105.38	209.29	349.88	
Empty	- 1.01	6.22	19.57	39.64	66.43	98.61
ROADRAILER						
Two	- 5.62	34.04	110.56	215.04	315.82	426.08
Two with skirt	- 6.11	34.43	115.58	232.32	334.28	452.78

TABLE 5

ROLLING MOMENT VOLUME

(ft.^{3})

For 1 or 2 units as specified - moment taken about top of rail

	YAW ANGLE 0	6	12	18	24	30
UNITS ON BALANCE						
<u>SANTA FE</u>						
45 ft. trailers, facing forward						
Leading, middle	- 13.9	444.8	1200.7	2223.3		
Middle, middle	- 61.5	361.0	978.6	1964.7	2945.2	
Middle, trailing	-109.7	277.8	888.7	1863.3		
40 ft. trailers, facing forward						
Leading, middle	- 63.3	399.1	1304.6	2370.6		
Middle, middle	- 82.2	377.0	900.8	1813.6	2831.3	
Middle, trailing	- 96.2	265.8	784.9	1618.3		
45 ft. trailers, facing backward						
Trailing, middle	- 12.1	376.8	1154.5	2139.3	3401.3	
Middle, middle	-110.6	375.0	913.4	1779.7		
Middle, leading	-103.8	339.3	822.3	1674.3		
40 ft. trailers, facing backward						
Trailing, middle	-123.8	335.4	966.9	1859.1	2993.6	
Middle, middle	- 80.0	309.8	727.1	1460.4	2375.1	
Middle, leading	- 89.3	363.0	789.6	1569.3		
Empty						
Leading, middle	- 2.4	2.8	23.1	58.5	124.7	
Middle, middle	- 6.6	9.4	4.1	32.2	79.5	147.3
Middle, trailing	5.8	7.8	35.6	77.0	142.8	235.2

TABLE 5 (continued)

	YAW ANGLE					
	0	6	12	18	24	30
UNITS ON BALANCE						
<u>PATON LO PRO</u>						
40 ft. trailers, facing forward						
Middle, middle	- 63.4	306.3	798.9	1472.0	2345.0	
Trailing, leading	- 29.3	289.3	861.9	1631.0	2651.0	
45 ft. trailers, facing forward						
Middle, middle	- 74.0	323.0	902.6	1583.9	2334.1	
Trailing, leading	-119.0	330.3	897.9	1774.5	2793.4	
40 ft. trailers, facing backward						
Middle, middle	- 64.0	256.5	629.5	1269.3	2130.9	
Leading, trailing	- 71.4	316.7	855.2	1685.1	2836.7	
45 ft. trailers, facing backward						
Middle, middle	- 90.4	307.0	815.8	1625.0	2569.4	
Leading, trailing	- 31.3	288.2	781.3	1525.3	2536.4	3791.5
Empty						
Middle, middle	- 4.9	22.0	85.3	182.7	308.4	426.3
Leading, trailing	- 6.1	26.9	94.1	191.7	347.8	536.2
40 ft. containers						
Middle, middle	- 32.7	202.3	581.2	1137.8	1867.9	
Trailing, leading	- 28.1	202.8	610.4	1245.4	2125.9	
35 ft. containers						
Middle, middle	- 33.7	189.4	517.5	1078.6	1808.1	
Trailing, leading	- 29.9	182.2	540.3	1182.8	2202.1	

TABLE 5 (continued)

	YAW ANGLE					
	0	6	12	18	24	30
UNITS ON BALANCE						
SOUTHERN PACIFIC ARTICULATED DOUBLE STACK						
Two 40 ft. containers						
Middle	- 30.3	354.8	972.2	1797.3	2774.3	
Trailing	-104.1	337.2	886.0	1717.5	2611.7	4137.8
Leading	-108.7	443.7	1099.6	2169.3	3805.5	
One 40 ft. container						
Middle	- 19.4	68.4	213.8	439.0	691.6	983.8
Trailing	- 25.4	54.2	193.9	422.5	645.9	937.6
Leading	- 20.1	76.7	263.6	553.3	891.3	1262.6
Empty						
Middle	2.1	53.3	176.4	360.4	550.8	755.1
Trailing	- 6.9	44.1	162.5	335.3	528.8	728.2
Leading	- 1.3	6.2	214.1	421.7	632.2	840.5
TRAILER TRAIN PROTOTYPE						
Two 45 ft. trailers						
Facing forward	-116.5	455.7	1181.3	2060.3	3104.8	
Facing backward	- 74.1	377.8	988.8	2010.6	3428.9	
Two 40 ft. trailers						
Facing forward	- 58.8	401.6	1053.2	1970.4	3051.2	
Facing backward	- 69.4	375.3	843.4	1712.3	2910.1	
Empty	7.2	62.1	62.8	120.1	194.3	280.2
ROADRAILER						
Two	- 35.1	237.2	772.7	1542.1	2291.3	3110.1
Two with skirt	- 36.2	255.8	836.8	1691.2	2456.2	3362.3

APPENDIX A

RELATIVE WIND

The aerodynamic effects on the train depend upon the relative velocity of the wind with respect to the train. This velocity can be caused by either the wind over the ground or the motion of the train. The relative wind is found from a vector addition of these two quantities as shown in Figure A-1. The relative wind and yaw angle can be calculated using the following relations.

$$V_R = \sqrt{(V_w \sin\alpha)^2 + (V_t + V_w \cos\alpha)^2}$$

$$\psi = \arctan\left(\frac{V_w \sin\alpha}{V_t + V_w \cos\alpha}\right)$$

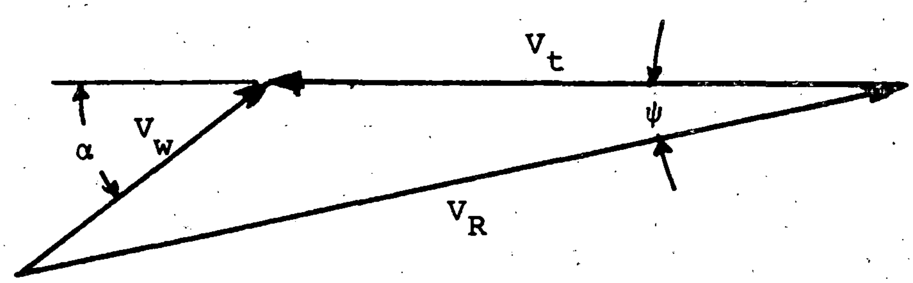


Figure A-1. Diagram Illustrating Relative Wind as Determined by Actual Wind and Train Speed.

APPENDIX B

COMPARISON BETWEEN PRESENT TESTS AND PREVIOUS TESTS OF TTX CAR

A large number of tests were run in Reference 1 to determine the aerodynamic properties of trailers and containers on TTX cars. In the present series of tests a check run was made of one of the configurations to determine if the previous results would be reproduced by the present series of tests. The purpose of this check was to make sure that the tests in both series were being run in the same way and that uncontrolled differences had not occurred that would cause different results to be obtained. The comparison is shown in Figure B-1. Results for the TTX car loaded with two trailers in both the forward and in the backward directions are shown from the previous tests and the check run for trailers run in the backward direction from the present series. Unfortunately, at the higher yaw angles contact existed between the metric car and the fixed ground plane. The presence of such contacts is monitored by electrically isolating the metric assembly from the fixed assembly and monitoring the electric resistance between the two. While this system did not indicate contact until the 24° yaw angle was reached, the axial force area results show a leveling off after the 12° yaw angle measurement. The previous and present results seem to agree well up to the 12° yaw angle point but, as the yaw angle continues to increase, the present results do not continue to rise as do the previous results. The explanation would seem to be that the discrepancy is caused by the contact between the metric and stationary parts. The agreement at the low yaw angles is a good substantiation that the two sets of wind tunnel results are in agreement. It is unfortunate that it was not possible to repeat this check and determine whether the proposed explanation is valid.

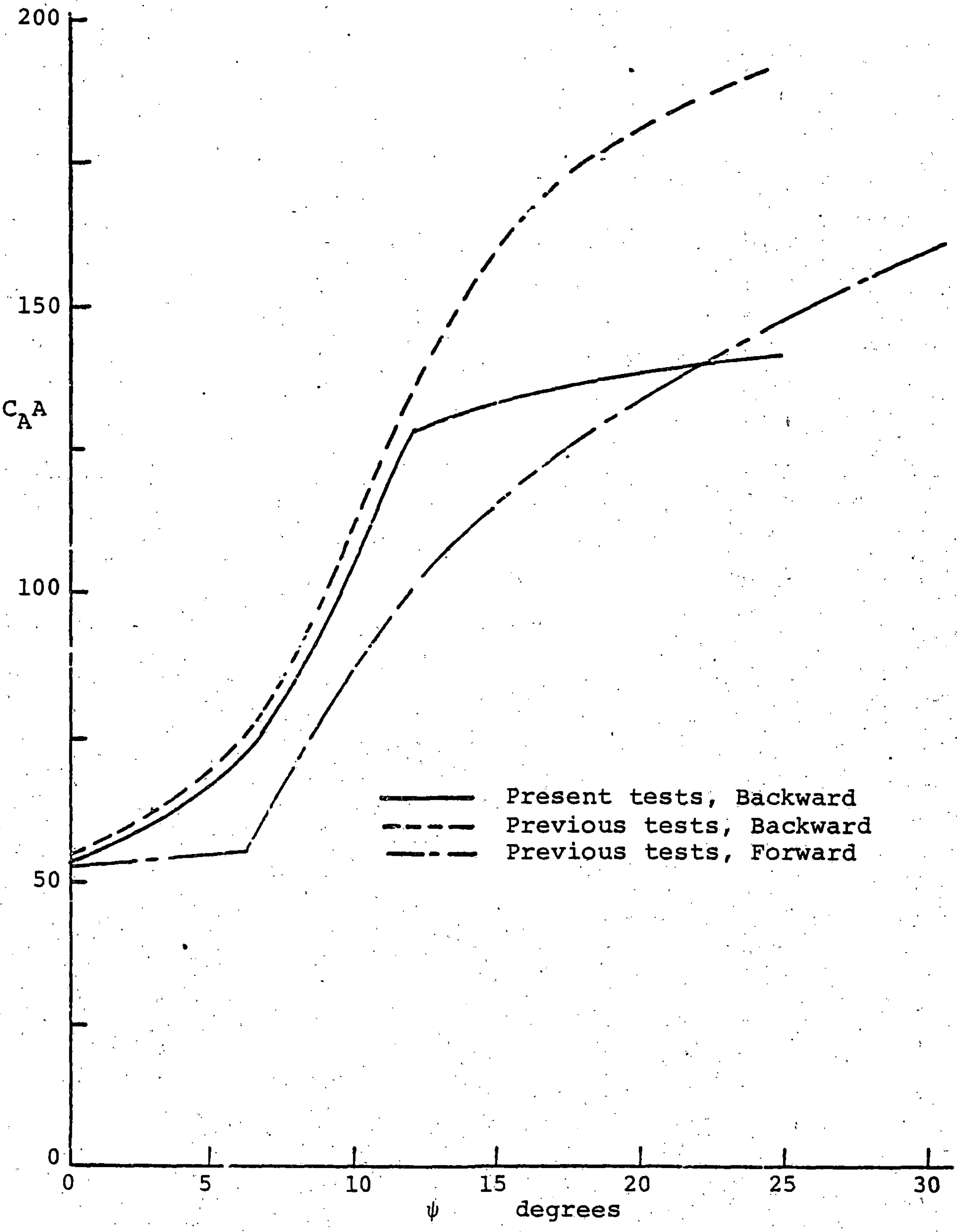


Figure B-1. Comparison of Axial Force Area as a Function of Yaw Angle for Present and Previous Tests of TTX Cars.

APPENDIX C

GROUND PLANE EFFECTS IN WIND TUNNEL TESTING

The aerodynamics of a vehicle near the ground are different than those of a vehicle far from the ground. This difference is called ground effect. For purposes of understanding, aerodynamic phenomena are usually classified as viscous and inviscid. Inviscid phenomena are those in which the viscousity of the air is not important and viscous ones, ones in which the viscousity is important. Viscous effects are usually limited to the region near a solid surface, the thin layer along this surface which is called the boundary layer.

Inviscid Ground Effects

Inviscid ground effects are caused by the fact that the air disturbed by the passage of the body is prevented from crossing the ground plane. This effect can be of considerable importance. For instance, a cylindrical body with a component of flow perpendicular to the axis will have zero lift far from the ground but will have considerable lift close to the ground. Measurements that substantiate this statement are given in References 3 and 4. The reason is that away from the ground the air flows symmetrically around the cylinder but near the ground most of the air must flow over the top. The effect upon axial force is less pronounced than on lift. It can be expected to be greatest for bodies of approximately the same height as width and be small for bodies which have one of these dimensions much larger than the other. The axial force on a body with approximately equal dimensions is lower than when one dimension predominates (a sphere has a lower drag coefficient than a cylinder). The inviscid flow about a body on the ground is the same as that about a body made up of the original body and its image in the ground plane when this new body is located far from the ground. If the body is already long enough so that the flow field is similar to that for a width to height ratio of zero or infinity, a change in either of these dimensions by a factor of two will have little effect. However, if the dimensions are about equal, a change in one of the dimensions by a factor of two is an important change of shape.

These inviscid effects are the ones which can be properly satisfied in wind tunnel tests and are the reasons for using a ground plane or equivalent.

Viscous Effects

The viscous effects of ground effect are not easily satisfied in wind tunnel tests. Viscous effects cause a shear force on the air in a direction to oppose motion between the air and the solid surface. A ground vehicle moves with respect to the ground and it is difficult to simulate this motion of the ground with respect to the vehicle in the wind tunnel. This situation has been discussed in Reference 1 (especially pages 21-22). The easiest solution is a ground plane stationary with respect to the model. This represents the poorest simulation of the viscous ground plane effects of the different methods to be discussed, since the wall shear force is in the wrong direction, but does not introduce any additional problems. Another technique is the use of two models, the actual and an image model. Here symmetry requires that the image plane be a streamline and no shear forces are introduced by the wall since there is no wall. (It is assumed that the model and image are far enough apart so that the boundary layer on the image model does not effect the actual model.) The third technique is to use a ground plane consisting of a moving belt. If the belt is run at the speed of the flow it properly simulates a ground vehicle moving over the ground into still air. The viscous shear forces on the ground plane then act to maintain the air speed at its undisturbed value. This last method is a correct simulation to the actual situation. Its disadvantages are that it requires a special piece of equipment, that the belt height is hard to control precisely, and that the model cannot be supported from the ground plane.

At least two investigators, References 4 and 5, have attempted to evaluate the errors caused by these different techniques by comparing the results found by using the different methods on the same models. These measurements show that the differences between the techniques are small and there was not a consistant trend between the different techniques. If the moving belt technique is assumed to give the correct answer, the image method does not appear to be superior to the fixed ground plane technique. The conclusion drawn from these studies is that only in special circumstances is a technique other than the fixed ground plane justified.

Boundary Layer Considerations

A calculation of the boundary layer for the series of freight car tests run in the CIT wind tunnel was given in Reference 1 and repeated here as Figure C-1. This figure shows that the boundary layer is an appreciable fraction of the height of the unloaded multimodal cars recently tested. It is not until quite close to the wall that the boundary layer velocity drops appreciable from free stream velocity (0.8 free stream velocity at 0.2 of the boundary layer height from the wall). Figure C-2 shows the Trailer Train Prototype car loaded with a trailer and the calculated boundary layer thickness at the location of the metric car.

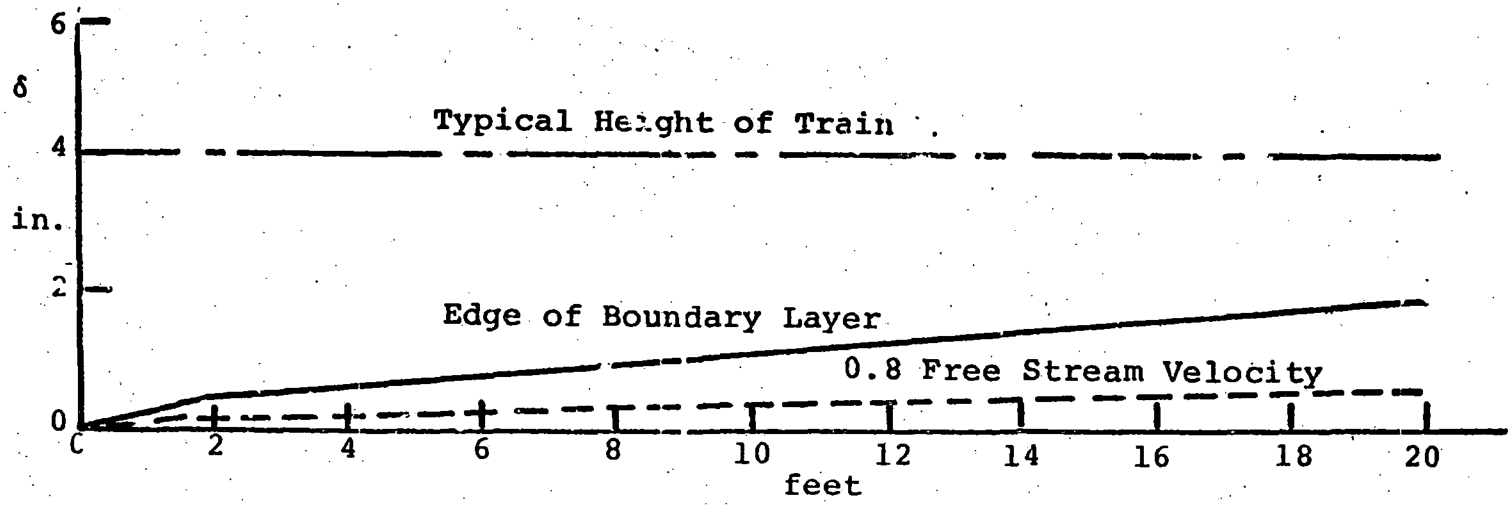


Figure C-1. Boundary Layer on Ground Board Compared With Train Height.

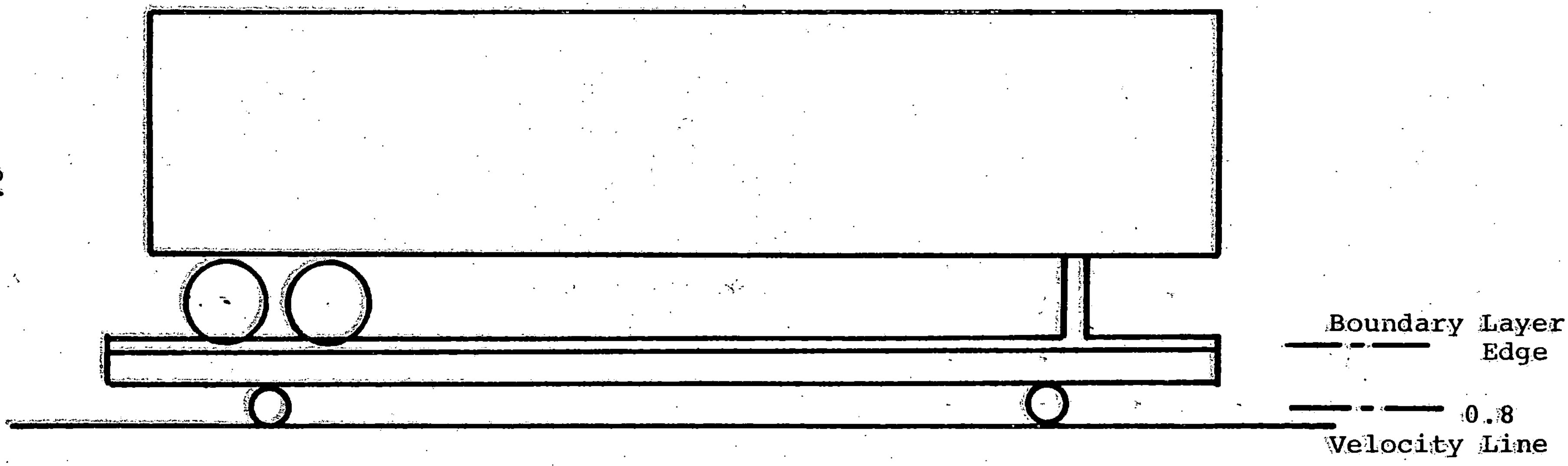


Figure C-2. Boundary Layer Heights Shown in Comparison With Trailer Train Prototype Car Loaded With Trailer.

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